STUDY OF FACTORS INFLUENCING ERODIBILITY OF SOILS IN UNLINED EARTH CHANNELS IN THE SANTA CLARA VALLEY

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CONSULTING ENGINEERS AND GEOLOGISTS

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STUDY OF FACTORS INFLUENCING ERODIBILITY OF SOILS IN UNLINED EARTH CHANNELS IN THE SANTA CLARA VALLEY

PREPARED
FOR

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March 5, 1971
Project JS 11899

Santa Clara County
Flood Control & Water District
516 East Martha Street
San Jose, California

Gentlemen:

We have made a study of factors which influence the erodibility of soils forming the periphery of unlined earth channels in the Santa Clara Valley. This work was performed pursuant to Work Order Number 81206 issued by the Santa Clara County Flood Control & Water District.

Our purpose was to study the erosion existing in unlined flood-control channels and the associated soil conditions. Based on the results of this study, recommendations have been formulated for a design procedure to predict and limit erosion of unlined-channel banks. The accompanying report contains our conclusions and recommendations as well as the results of our field investigation and laboratory tests.

During this study George M. Sicular, Professor of Civil Engineering, San Jose State College, served as a consultant. He contributed specifically toward evaluation of hydraulic factors and with critical literature appraisals.

Very truly yours,

William A. Bischoff

William A. Bischoff
Project Engineer

Reviewed by

Robert S. Wright

Robert S. Wright
Senior Project Engineer

WAB:bb

CONTENTS

Page

LETTER OF TRANSMITTAL

INTRODUCTION 1

CHANNEL INSPECTIONS

Ross Creek 2
Calabazas Creek 3
Sunnyvale East Channel 4
Smith Creek 5
Sierra Creek 5
Golf Creek 6

CHANNEL DETERIORATION

Erosion 6
Slope Failure 10
Channel Design 11

RECOMMENDATIONS

Design 12
Construction 16

AREAS FOR FUTURE STUDY 17

CONCLUDING REMARKS 19

APPENDIX A

Literature Review A-1
Regime Theory A-1

APPENDIX B

Existing Design Techniques B-1

FIGURES 1 THROUGH 6 - LIMITS OF CHANNEL INSPECTION

FIGURES 7 THROUGH 10 - PHOTOGRAPHS OF CHANNEL CONDITION

FIGURE 11 - LIMITING TRACTIVE FORCES FOR FLAT CHANNELS OF INFINITE WIDTH

FIGURE 12 - ACTUAL MAXIMUM TRACTIVE FORCE (T_b) ON BED OF STRAIGHT TRAPEZOIDAL CHANNELS

FIGURE 13 - ACTUAL MAXIMUM TRACTIVE FORCES (T_S) ON SIDES OF STRAIGHT TRAPEZOIDAL CHANNELS

FIGURE 14 - ALLOWABLE TRACTIVE FORCE VERSUS PLASTICITY INDEX

FIGURE 15 - ALLOWABLE TRACTIVE FORCES VS. SOIL GRAIN SIZE (BY WOODWARD-LUNDGREN & ASSOCIATES)

FIGURES 16 THROUGH 26 - SOIL GRAIN SIZE DISTRIBUTIONS

TABLE I - SOIL CLASSIFICATIONS & LABORATORY TESTS

TABLE II - VELOCITIES AND TRACTIVE FORCES OF SANTA CLARA COUNTY FLOOD CONTROL AND WATER DISTRICT CHANNELS

ERODIBILITY OF SOILS IN UNLINED EARTH CHANNELS IN THE SANTA CLARA VALLEY

INTRODUCTION

Unlined flood control channels in the Santa Clara Valley have been continually eroding. Channel deterioration of this type has presented problems of right-of-way encroachment and loss of hydraulic characteristics. This report summarizes a study made of the soil erosion phenomena. The study was limited in scope to an investigation of the erodibility of soils in straight unlined channels.

To determine the state of the art of stable channel design, a brief literature review was made. In addition, existing design techniques used by the District and those used by other government agencies were investigated. These items are included in appendixes to this report.

Visual examinations were made of several selected channels within the District's jurisdiction. Soils exposed in the channel banks were sampled, classified and tested in our laboratory. Soil types and properties were correlated with existing channel condition and with estimates of maximum water velocities.

Several factors influencing deterioration of unlined channels were apparent from this study. Firstly, maximum water velocities occurring during peak flows are creating forces on the channel surfaces which exceed the resistance of the channel soil materials. Secondly, slope instability was observed as a major cause of channel deterioration. Piping through channel banks and soil shrinkage were observed to contribute to slope instability.

Recommendations for future channel design are contained in the following sections along with suggested areas for future study and research.

CHANNEL INSPECTIONS

Six channels within the Santa Clara Valley were inspected and sampled. Erosion was noted in all channels to varying degrees. Inspections were limited to channel banks as bed-load covered all channel bottoms. In this report, the degree of erosion is defined as follows:

1) Negligible - Less than 3 in. of soil eroded from bank. Channel practically remaining in an "as-built" condition.
2) Slight - 3 to 12 in. of soil eroded from banks.
3) Moderate - 1 to 3 ft of soil eroded from banks.
4) Severe - More than 3 ft of soil eroded from banks.

Following are descriptions of each channel inspected. A detailed description of soil samples, laboratory test results, and estimated maximum flow quantities are contained in Table I and Table II.

Ross Creek (Improved in 1956)- Ross Creek was inspected between Camden Avenue and the Almaden Road as shown in Figure 1. Channel soil materials consist of dense sandy gravel deposits alternating with light brown silty clays along the channel length.

Overall erosion can be classified as slight to moderate. The majority of erosion has occurred within a depth of approximately 0 to 4 ft from the existing channel bottom. Erosion has occurred in uniform sheet-like sections triggering some slides in the channel banks. Some undercutting of channel banks was also noted. Most banks of the channel have not experienced large landslides and are not encroaching upon adjacent property. Where banks are comprised of a composite section of clay and gravel, the clay displays the greater amount of erosion. Photographs showing slight to moderate erosion typical of Ross Creek are shown in Figure 7.

Severe erosion was noted where an abrupt change in the bank material occurred. Such changes consisted of riprap lining used to protect subdivision storm-drain inlets, concrete drop structures, etc.

Calabazas Creek (Improved 1957) - Calabazas Creek was inspected from Benton Avenue to about 1000 yards north of the Bayshore Freeway as shown in Figure 2. In the reaches from El Camino Real to the Bayshore Freeway, the natural surface soils generally consist of 2 to 3 ft of black silty clay of high plasticity. This material is underlain by a light brown sandy clay containing various amounts of lime cementation. Sand quantities within the clay vary from location to location. In some areas, particularly at the toes of the slopes, the sand becomes the predominant material. Old creek deposits of cohesionless sand and gravel are present intermittently in the channel banks.

Severe erosion has been observed in the improved section. A typical eroded section is shown in Figure 8. Most channel deterioration has been caused by slope failures. Material sliding or falling from the banks has been carried downstream as bed-load and suspended solids. The resulting channel banks have been eroded to vertical slopes encroaching upon adjacent property at many locations.

Seepage was detected at the toe of the channel slopes in many areas. Undercutting of the slope has occurred particularly where fine sandy materials were present. Large, deep, shrinkage and tension cracks were noted on the sides and tops of the channel slopes in soils of high plasticity. The surfaces of the clay banks have dried, shrunk, and have formed shallow, alligator-type, cracking patterns extending to depths of 3 to 5 in. These shallow cracks should not be confused with the deep shrinkage and tension cracks.

The banks of the Calabazas between Benton Avenue and Pomeroy have also experienced similar deterioration. Compacted gravelly clay fill was used to construct most of the channel banks between Benton Avenue and the downstream drop structure. The slopes have deteriorated to vertical banks and are infringing upon adjacent properties.

North of the Bayshore Freeway, soft, blue-gray very silty clay marine deposits were detected near the channel bottom. Fill and natural sandy clay soils were observed above the marine deposit. Erosion and bank collapses were noted in this area.

Sunnyvale East Channel (Improved 1966) - The Sunnyvale East Channel was visually inspected from the El Camino Real to about 1000 yards north of the Bayshore Freeway as shown in Figure 3. The natural soil conditions and deterioration problems are very similar to those of the Calabazas. Black plastic sandy clay top soil overlies light brown sandy clay deposits containing some lime cementation. Fine sand and gravel deposits are in evidence at various locations along the channel. These deposits are probably the remains of the natural creek bed.

Serious degradation of the channel slopes has been caused by slope failures. Clay banks have sloughed to vertical slopes. Gravel and sand banks have eroded but generally have not sloughed. Consequently, erosion of gravel banks is less severe than the erosion of clay banks. The difference in erosion is shown in Figure 8.

Piping has occurred through granular soils and, in many instances, is believed to have been the cause of undercutting of channel banks. Some dried clay banks were observed to have sloughed into the channel bottom. Evidence of sloughing is also shown in Figure 8.

Smith Creek (Improved 1964) - Smith Creek was inspected from Elam Avenue to San Tomas Aquino Road as shown in Figure 4. The channel banks are composed of sandy clays interspersed in some locations with sand and gravel deposits.

Erosion of this channel is classified as slight. A general sheet-type of erosion has occurred, not yet precipitating slides within the banks themselves. Typical erosion is shown in Figure 9.

Sierra Creek (Improved 1967) - Sierra Creek was inspected from Berryessa Creek to Furlock Drive as shown in Figure 5. Throughout most of the straight alignment paralleling Morrell Avenue, the predominate soil cross section consists of about 3 ft of black, silty clay topsoil overlying a deposit of light brown, silty clay to clayey silt of low plasticity. Intermittent deposits of sand and gravel were also observed. Most of the channel is covered with grass and vegetation.

Erosion of this channel is classified as slight and limited to the bottom 3 to 4 ft of channel. No major bank failures were noted. The presence of flowing water in the creek during inspection precluded detection of piping through channel banks. Typical channel condition is shown in Figure 9.

Golf Creek (Improved 1965) - Golf Creek was inspected between the Almaden Expressway and Culligan Boulevard as shown in Figure 6. Although no actual soil sampling was done, a qualitative evaluation of the soil conditions has been made. The materials exposed within this channel varied from silty clays to dense clayey sand-and-gravel deposits. Erosion, which has occurred to varying degrees, can generally be classified as moderate.

Some soil bank erosion has occurred and has precipitated landslides infringing upon private property. It is estimated that in the near future additional sliding will occur within the clay deposits causing property boundary problems. On the average, bank slopes have eroded to a 1 to 1 inclination. (See Figure 10).

CHANNEL DETERIORATION

Examinations of straight channel sections indicate deterioration is occurring to varying degrees in all channels. One cause of channel deterioration is erosion. A second cause of channel deterioration is bank instability. These items and other causes of deterioration are discussed in the following sections.

Erosion - Erosion is defined as the wearing away of soil by the shearing action of water moving over the channel surface. Shearing stresses created by flowing water are called tractive forces. Erosion caused by tractive forces is resisted differently in various soil types. Both the creation of tractive forces and soil resistance to tractive forces are discussed below. The tractive force concept appears to be the most valid approach to analysis of channel erosion. In the past, the District has used the allowable water velocity approach. Water velocities are also discussed in the following sections for comparison with channel erosion.

a) Tractive Forces & Water Velocities - Field observations indicate that excessive tractive forces and/or velocities have occurred in the channels inspected. This is apparent from the evidence of channel erosion. In an attempt to define the erosive forces, estimates of the maximum developed tractive forces and channel water velocities have been made from recorded maximum flows. These estimates are presented in Table II.

To make these calculations, it was necessary to assume an as-built channel cross section and bottom slope. Calculated tractive forces were also based on recorded maximum flow depths and soil grain sizes. Soil grain sizes, as determined by laboratory tests, are presented in Figures 16 through 27. Where soil grain sizes have not been determined, estimates have been made for calculation purposes.

Calculated tractive forces are based on a modification of Lane's/[16] technique as defined in Appendix A. Lane's equation yields low (calculated) tractive forces for fine grain soils. Recommendations are contained later in this report to impose a limit upon this equation and to provide realistic friction factors for these fine grain soils.

Based upon a modification of Lane's equation with new recommended limits, maximum tractive forces have been calculated and are summarized in Table II. For the channels studies (except Smith Creek) all calculated tractive forces exceed the allowable for stable channels. (Allowable tractive forces are discussed in the following section)

Calculated maximum channel velocities are also presented in Table II. Although the tractive force method of analysis provides a more direct procedure for evaluation of channel erosion, maximum channel velocities have been compared with "allowable velocities" to provide generalized empirical evaluations. Allowable channel velocities in Table II are those presented in Technical Release #25 prepared by the United States Soil Conservation Service./[23]

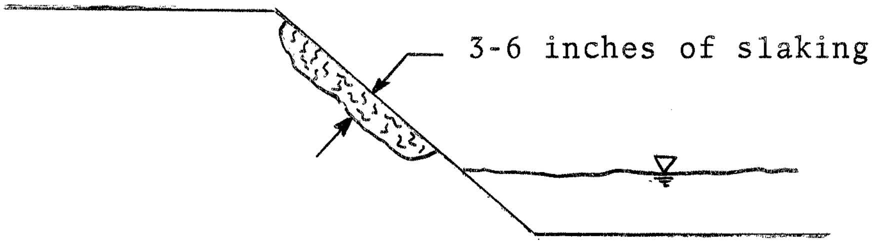
Excessive tractive forces and/or channel water velocities are created primarily by excessive channel bottom slopes. Design velocities of 8 ft per second used by the District in the past have been excessive and have developed excessive tractive forces. Siltation and bed-load have further increased channel gradients which increased the already excessive tractive forces. This effect was studied during the heavy flows of January 1969 in San Tomas Creek by Mr. Edwin Ferguson, Senior Design Engineer for the District. It was reported that materials were deposited below drop structures steepening the bottom slope to something near the original channel configuration. This in turn resulted in excessive tractive forces and consequent channel erosion.

b) Resistance to Erosion - Based on our observations, it is apparent that resistance to tractive forces is developed differently in cohesive and non-cohesive soils. In cohesionless soils, erosion or particle removal occurs when the tractive forces created by flowing water are sufficient to lift the particle and transport it downstream. Resistance to the erosion, therefore, is provided by particle weight and interparticle friction. Usually erosion of cohesionless soils occurs in the form of sheet-type soil removal in long uniform strips.

Cohesive soils provide resistance to erosion by virture of their cohesive strength. Interparticle bonding of the clay materials provides this strength. Erosion of clay materials occurs when the interparticle bond forces (cohesion) have been exceeded or weakened. The particles then become suspended in colloidal forms. Particles in over-consolidated clays at natural moisture contents normally are held in place by relatively high interparticle forces and consequently offer high resistance to tractive forces.

If dried, cohesive materials develop high strengths. Highly plastic materials form exceptionally high interparticle bonds when drying occurs. This drying-induced bond (cohesion) is not a permanent strength increase and rewetting of cohesive soil will destroy the interparticle bond resulting in a loss of strength. Where the bond is nearly destroyed a cohesionless suspension of fine-grained particles results and the "slaked" particles are particularly vulnerable to tractive forces and erosion.

Based on field observations, it is estimated that depths of 3 to 6 in. of slaking occur on channel sides during normal seasonal changes. This depth of soil is easily and quickly eroded from the channel bank by either high water flow or rainfall.

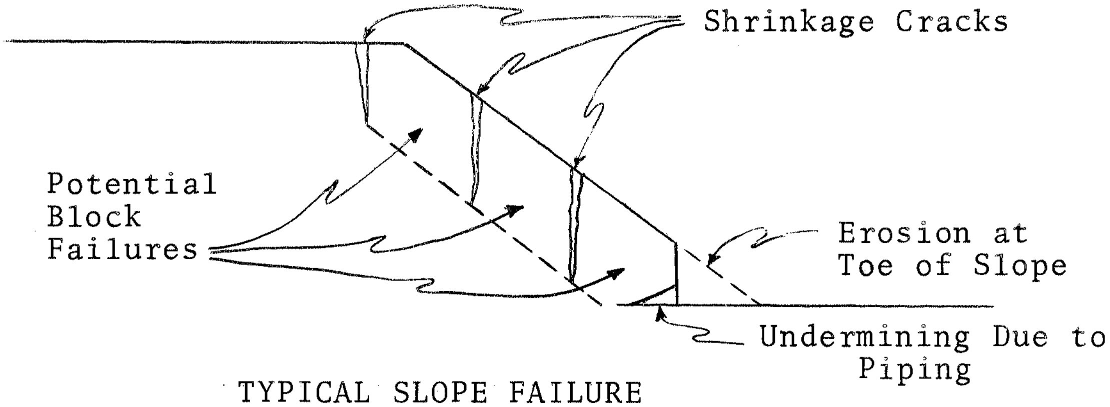


SLAKING

Slope Failure - Slope failures in clay soils appear to be the main cause of property encroachment in flood-control channels. These slope failures may be defined as large masses or blocks of soil which slide or fall from the banks into the channel bottom. Slope failures create a pockmark appearance on the channel sides, generally leaving near vertical side slopes.

The mechanism of slope failure is a progressive one in which the toe of the slope is first worn away by both erosion and/or piping. Piping usually occurs in fine-grained, cohesionless materials. Ground water flow from an adjacent area into the channel tends to loosen the soils through which it flows. At the toe of the channel slope, high seepage gradients are created. Because these high gradients saturate and loosen the soils, tractive forces created by flowing water easily erode the toe of the slope which in turn precipitates slope failures.

Tension cracks, caused by drying, create additional slope instability. When these cracks become filled with water or are extensive enough to lessen the strength of a slope below that necessary to hold the material, a slope failure occurs. The material then falls into the creek channel and is carried away. This type of slope failure is different from the usual circular arc failure assumed in channel design.



TYPICAL SLOPE FAILURE

Based on our inspections, it appears that slope failures create the major problems of channel deterioration. Slope failures remove the largest volume of material and are the primary cause of property encroachment.

Channel Design - Determination of the soil conditions along a proposed channel is an important part of design. Soil types are often variable along natural channel beds due to meandering of the stream and subsequent deposition of different materials. Recent stream deposits are usually loose and weak.

The District presently evaluates the soil conditions along a channel alignment from exploratory borings made on about 1000 foot centers. Laboratory tests are made on soil samples to determine grain-size distribution, plasticity index and shear strength.

Average soil conditions, as are being used across a given soil cross section, result in unconservative channel designs. For example, the soil cross section along a District designed, unlined channel improvement consisted of a stiff silty clay underlain by a low-plasticity silt at a depth of about 3/4 the channel depth. The silty clay, being the predominant material, was used for design considerations; however, the silt material, which has the lesser resistance to tractive forces and erosion, is located in the area subject to the major flow. In this same case example, a uniform soil condition was assumed for slope-stability calculations when a non-uniform and weaker actual condition existed. Greater attention should be given to details of the soil-profile.

Alteration of Flow Characteristics - Erosion was also observed due to channel irregularity (such as curvature, change in channel roughness, etc.) that alter the flow characteristics. Water passing over a change in channel roughness or channel irregularity causes a vorticity effect which creates flow into or away from the channel bank rather than parallel to it. This type of flow has a great eroding potential.

RECOMMENDATIONS

Design - An important part of design is the recognition of soil conditions along any proposed alignment. It is recommended that the existing exploration program of borings on 1000-foot centers be continued for minor projects. On major projects, where right-of-way consideration are more important, boring spacing should be decreased to 500-foot intervals. Where improved channel alignments follow existing natural channels, a complete soil and geological reconnaissance of existing banks should be made. Laboratory tests should be made to determine the Atterburg Limits and grain-size distribution. Shear-strength tests should also be made.

Based on the field investigation and laboratory tests, typical soil cross sections should be drawn for each interval investigated. The susceptibility of each soil to tractive forces and each soil position within the channel section should be studied. The same factors should be considered in slope stability calculations. Field inspection during construction should be made to verify the anticipated soil conditions and to detect any undesirable conditions which might be present.

It is recommended that a tractive-force design procedure be used for future channel improvements. A tractive-force analysis is one of successive trials. A trial channel section must first be designed from which the tractive forces can be calculated. These calculated forces should then be checked against the allowable tractive forces for the particular soil material. If the developed tractive forces exceed the allowable, a second, or possibly a third, trial section must be designed.

For a first estimate of channel design, it is recommended that an allowable velocity be selected from the charts and table on Figure 6-1 of the Soil Conservation Service Manual TR-25./[23] Actual developed tractive forces should then be calculated. For soils with a D_{75} particle size greater than 1/4 inch, developed tractive forces can be calculated by the technique recommended by Lane./[16] This technique is described under the "Literature Search" Appendix of this report. With Lane's technique, an equivalent Manning's "n" associated with soil-water friction is determined by the following equation:

$$n = \left(\frac{D_{75}}{39}\right)^{1/6}$$

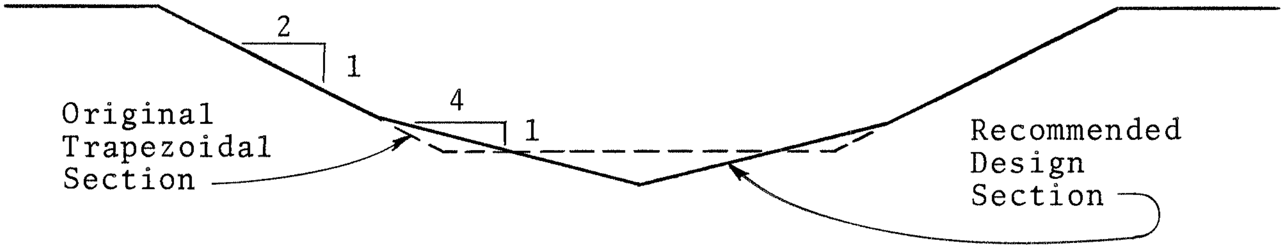
n = Equivalent Manning's "n"

D_{75} = Soil particle size of which 75 percent of soil sample is smaller.

Extrapolation of this relation to soils with D_{75} less than 1/4 inch produces unrealistically low values. For example, in channels without vegetation, the impedence to flow due to soil friction can be calculated to be as low as 30 percent of the total over all impedence. This relation is obviously unrealistic. As a limiting value, it is recommended that the equivalent Manning's "n" used to calculate developed tractive forces should not be less than 85 percent of the total Manning's "n" used for channel design. After the developed tractive forces have been calculated, the soil allowable tractive forces should be determined from Figure 15 of this report. This figure is based on a compilation of the work of Lane,/[16] Dunn,/[6] Smerdon & Beasley,/[26] and the Soil Conservation Service/[23] which has been adjusted based on the results of this study.

The values given for fine-grained soils should limit erosion provided that the clays are maintained at their natural moisture content. Clay banks subjected to cyclic wetting and drying will slake. Slaking depths of 3 to 6 in. per season should be expected unless some means is employed to prevent loss of natural moisture. Drying might be prevented by polymer sprays or other compounds. This is an area in need of future study.

It has also been noted that most erosion begins at the toe of slopes, eventually causing slope instability. An increase in channel longevity might be attained by changing the trapezoidal channel cross sectional shape to the configuration shown below:



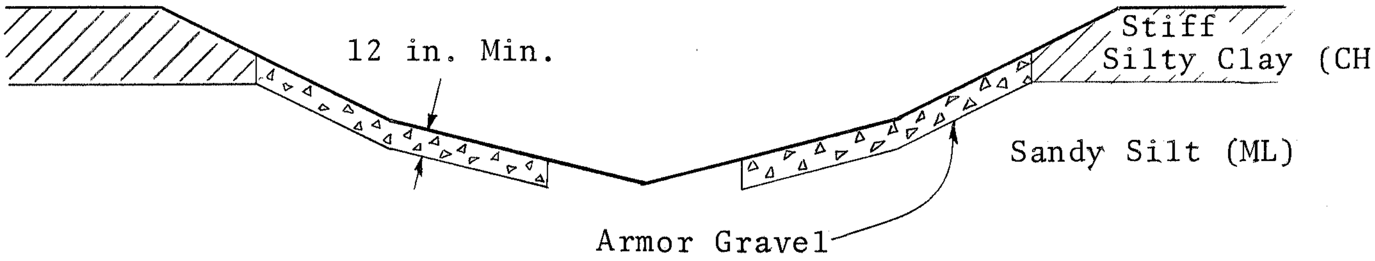
This configuration would confine low flows to the center of the channel and would require that a larger volume of material to be eroded before an unstable bank is created.

In areas where fine cohesionless soils are exposed at the toe of the channel bank, piping conditions could develop due to ground water seepage. Soils having the following material properties should be considered susceptible to piping:

$D_{50} < 1.0$ mm D_{50} = Particle size of which 50% of soils is finer.

Plasticity Index $<$ 15

The effects of piping could be minimized by excavating these fine-grained soils and replacing them with a pervious blanket of armor gravel and filter material as shown below.



The armor rock blanket should be a well-graded filter material having the following gradational restrictions:

$$5\text{mm} < D_{85} < 75\text{mm}$$

$$0.075\text{mm} < D_{15} < 1.1\text{mm}$$

This material should also have an allowable tractive force resistance sufficient to resist the developed tractive force at maximum flow. A minimum section of 12 in. of armor rock should be placed for protective purposes. This armor blanket is intended to stabilize fine-grained soils against piping and subsequent erosion and is not intended to be riprap. Riprap is usually well graded rock materials having a D_{15} size of 3 in. Where riprap is needed to resist scour such as on bends it should be placed on a bedding layer of sandy gravel filter material.

The gradational limits of the armor gravel are quite broad. It is anticipated that a material meeting these requirements might be found within most channel improvement areas making use of such material economically feasible.

Construction - If channel banks are constructed of compacted cohesive materials, compaction standards should be followed which would produce a soil structure least susceptible to swelling and shrinkage. Clay soils compacted dry of optimum have a relatively high swelling potential. Clay soils compacted wet of optimum have a relatively high shrinkage potential. Consequently, the most desirable compaction moisture content is very near the field optimum. Frequently the field optimum moisture content is slightly higher than the optimum moisture content determined by the California Field Impact laboratory compaction curves. For this reason, it is recommended that clay fills used for channel bank construction be compacted at a moisture content of 1 to 3 percent above the optimum as determined by the aforementioned laboratory test. Generally, clay soils should be compacted to a minimum relative compaction of 90 percent also based on the above referenced laboratory compaction test.

AREAS FOR FUTURE STUDY

The theory of tractive forces still contains many areas needing further study. The actual forces developed on channel boundaries should be more accurately defined. Lane's/[16] theory is based on a membrane analogy. The validity of this analogy is in question. Lane also defines the forces exerted on soil particles as a function of soil grain size. This relation does not appear adequate for fine-grained cohesive soils.

Developed tractive forces have been defined as a function of Manning's "n". Attempts should be made to define tractive forces as a function of more tangible factors. Einstein's bed-load functions might be one avenue for future study with respect to soil erosion. The effects of form roughness should also be considered as a possible cause of erosion.

The allowable tractive forces for fine-grained soils needs better definition and determination. Attempts in the past have been made to relate soil erosion to shear strength. A basic knowledge of soil mechanics indicates the validity of this assumption; however, all tests in the past have been made using soils of relatively low shear strength. Previous studies have also assumed an insitu constant shear strength when, in fact, the field soil shear strength varies as the water content varies. These areas merit additional research.

The foregoing items could be studied through the use of both laboratory and field experiments. A laboratory flume study is recommended to provide a better definition of developed tractive forces. An experimental channel constructed in the field could then be used to develop a relation between developed tractive forces and erosion or erosion rates.

Drying of clayey materials exposed on channel banks creates one of the most important problems associated with channel failures. Drying and rewetting of clay causes slaking and subsequent erosion. Drying also creates large tension cracks within a clay slope precipitating slope failures which account for the largest loss of materials and consequent property encroachment. It is recommended that plastics or other materials be studied to determine their suitability for sealing clay soils to eliminate the weathering effects. If clay soils could be kept at the natural moisture content, it is expected that slaking, cracking and loss of materials by slope disintegration could be reduced.

Other methods of increasing soil resistance to erosion should also be studied. Soil additives such as chemical stabilization, cement treating, or grouting are examples for possible research for practicability and economics.

Better methods of determining soil conditions along the alignment of a proposed channel improvement should be sought. As discussed with Mr. Ferguson of the Flood Control District, a statistical approach may prove practical. Conceivably, a statistical soil condition could be used for design. Channel-section design could then be altered to satisfy criteria of expected maintenance requirements. This is an area for which a sizable body of channel performance records correlated with soil types, hydraulic characteristics, flow volumes and velocities would be needed as a basis for statistical evaluation in channel design.

CONCLUDING REMARKS

It has been concluded that unlined channels are deteriorating in the Santa Clara Valley due to the creation of tractive forces greater than the ultimate tractive resistance of soils forming channel boundaries. Methods of estimating developed tractive forces and ultimate soil tractive force resistance have been proposed. The ultimate soil tractive force resistance of clay soils has been observed to be dependent on the soil water content. Cyclic wetting and drying of clays greatly reduces the tractive force resistance.

Slope instability has also been observed to be a major source of channel deterioration. Large chunks of channel banks have fallen into channel bottoms producing vertical banks. This type of slope failure is considerably different than the classical circular arc slope failure. Piping in fine-grained cohesionless soils near the toe of the channel bank has also decreased slope stability.

Determination of the soil conditions along a proposed channel alignment has been somewhat general in the past. Greater attention should be given to apparently minor details of the soil profile, particularly when soils are exposed to weathering elements and flowing water.

Based on this study and the conclusions mentioned above, recommendations have been given in this report for channel design to minimize soil erosion. In addition to the recommended tractive force method of analysis, recommendations have been given for the use of pervious gravel filter blankets to protect some soils against piping and for channel cross sectional shape. Recommendations have also been given for the compaction of clay soils. Many questions still remain unanswered regarding the design of stable channels. Some avenues of future research have been suggested in the latter section of this report.

APPENDIX A

LITERATURE REVIEW

An abundance of material has been written on the topic of stable channels. Only a brief review of pertinent contributions is described in the following section. A detailed Reference List considered during this study is contained as an appendix to this report.

REGIME THEORY

Stable channel design, as it is known today, was first studied in the 1890's by Kennedy/[14] while he was serving as an engineer in India. Kennedy developed the regime equation which defines a theoretical non-scouring non-silting water velocity of channels in a regime. This velocity is defined as an expotential function of the depth of flow as follows:

$$V = C\,(y)^m$$

V = design velocity
y = depth of flow
C = 0.84
m = 0.64

It was generally theorized that different channels should have different constants (C & m) which would properly describe the desirable velocities for various regimes.

Lacey/[15] followed in the footsteps of Kennedy and did additional work with regime equations. Blench/[3] and others are still experimenting and theorizing with regime equations, although more rational approaches are now gaining popularity.

Non Scouring Velocities for Soil Conditions - in 1926 Fortier and Scobey/[9] presented a detailed list of permissible channel velocities which did not produce scouring. These velocities were related to soil grain size. A considerable amount of information which closely paralleled the work of Fortier and Scobey, was also published during the same period by the Union of Soviet Socialist Republic./[27]

Tractive Force Analysis - The concept of tractive forces was first introduced by M. B. DuBoys/[5] in a paper presented in 1879. He theorized that the quantity of erosion of soil particles forming the perimeter of unlined channels should be a function of the shearing force exerted on the channel sides by flowing water. In 1955, Emory Lane/[16] of the United States Bureau of Reclamation developed a method for estimating the maximum developed tractive force on the bottoms and sides of channels. This method is based on Manning's equation:

$$Q = \frac{1.486}{n} r^{2/3} S^{1/2} A$$

n = Manning's roughness coefficient
r = Hydraulic radius
S = Energy gradient
A = Cross Sectional Flow Area

Generally, the total Manning's "n" for a channel reflects the overall impedence to flow including soil roughness, form roughness, vegetation, etc.

Lane's/[16] theory states that the frictional coefficient of water to soil particles is a function of the 1/6 power of the grain size.

$n_t = (D_{75})^{1/6}$

D_{75} = Soil Particle Size of which 75 percent of the soil material is finer.

n_t = Equivalent Manning's Coefficient.

Then to determine the energy gradient causing drag only on the soil particles, Lane/[17] proposed the following relation:

$$S_t = \left(\frac{n_t}{n}\right)^2$$

n_t = Manning's "n" relating to soil particles only

n = Total Manning's "n"

S_t = Energy gradient causing only soil-water friction

The preceding equations were developed for grain particle sizes between 1/4 in. and 5 in. It is estimated by the Soil Conservation Service/[24] that this theory can be extrapolated to smaller grained material with conservatism.

By relating the frictional characteristics of soil materials to Manning's equation, an effective energy dissipation through soil-water friction can be established from which the developed tractive force can be calculated. The developed tractive force on the bed of an infinitely wide channel is defined by the following equation:

$$T_D = \gamma d S_t$$

T_D = Tractive force developed (psf)

γ = Unit weight of water in channel (pcf)

S_t = Energy gradient causing only soil-water friction

d = Flow depth (ft)

Tractive forces developed on finite channel bottoms and sides are determined from Figures 12 and 13 as presented by Lane./[16]

Lane/[16] also proposed a method for estimating the maximum allowable tractive forces after which excessive soil erosion will occur. These allowable tractive forces are shown graphically in Figure 11. The allowable tractive forces are for flat beds and must be corrected when applied to channel side slopes. Lane's allowable tractive forces for cohesionless soils are well correlated to field performance and have proved to be successful indicators of erodibility. Allowable tractive forces for cohesive soils have not yet been defined successfully.

Irving Dunn/[6] presented a paper in June of 1959, proposing a method of estimating maximum allowable tractive forces for cohesive soils. Dunn/[6] related the allowable tractive force to shear strength, plasticity index, and grain size. Dunn's results are shown in Figure 14.

Smerdon and Beasley/[26] also presented a method of estimating maximum allowable tractive force as a function of plasticity index. Their equation is as follows:

$$T = 0.0034 \times PI^{(0.84)}$$

T = Allowable Tractive Force(psf)
PI = Plasticity Index

This equation is also plotted on Figure 14 along with recommended values developed by the U.S.B.R./[32]

Partheniades and Paaswell/[21] recently presented a paper reviewing recent efforts to define the erodibility of channels with cohesive boundaries. Several references made in this paper are of specific interest. Literature referenced to a Mr. Abdell Rahman/[1] summarized an attempt to correlate maximum allowable tractive forces to soil shear strength. Rahman found that slaking of clay soil caused erosion at very small tractive forces. Berghager and Ladd/[2] also noted this effect. Experiments by Grissinger/[11] indicate the erodibility of clayey soils to be a function of molding water content, compacted dry density, and clay mineralogy. Partheniades and Paaswell/[21] concluded that no satisfactory method had been developed for evaluating the erodibility of cohesive soils. Efforts to relate soil shear strength, plasticity index, or grain-size distribution to erodibility of cohesive soil are still inconclusive and inconsistent.

APPENDIX B

EXISTING DESIGN TECHNIQUES

Several local governmental agencies were contacted to determine the existing design procedures used to limit or eliminate erosion of unlined channels. Following is a summary of different agencies' design techniques:

Santa Clara County Flood Control & Water District - In the past, the District has arbitrarily selected a maximum allowable channel design velocity of 8 ft/sec. More recently, a tractive force evaluation technique has been adopted. Developed tractive forces are mainly determined from formulas listed in Technical Release No. 25 issued by the Soil Conservation Service./[23] These formulas were developed by Emory Lane/[16] in 1955. Methods for determining allowable tractive forces for cohesionless soils are also taken from the manual. To evaluate the allowable tractive forces for cohesive soils, the District makes reference to an article prepared by Irving Dunn./[6] Figure 9 of Dunn's paper presents several design curves relating grain size and plasticity index to allowable tractive forces. The design curve recommended by Dunn is shown for sake of comparison in Figure 14 along with curves developed by the United States Bureau of Reclamation/[32] in 1953. Dunn's recommended values are considerably lower than those of the U.S.B.R. The District now uses the U.S.B.R. curve for no vegetation. As a check on the tractive force evaluation, the District makes reference to the allowable design velocities presented in Technical Release No. 25/[23] in Figure 6-1.

Alameda County Flood Control & Water Conservation District - The Alameda District constructs most channels with concrete-lined sections. Where unlined channels are developed, limiting

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velocities of 8 ft per second have been used. The County is presently experiencing problems with erosion and, particularly, slope stability. It is also current practice of the District to hire outside consultants before channel construction when erosion problems are anticipated.

Contra Costa County - The majority of channels constructed in Contra Costa County are lined. For unlined channels, the County uses the design approach presented in Technical Release No. 25 of the Soil Conservation Service./[23] Erosion problems have occurred, some of which have been defined as piping in fine-grained cohesionless materials. Slope stability problems are also common.

U.S. Dept. of Agriculture, Soil Conservation Service - The Soil Conservation Service has developed, for their design purposes, Technical Release No. 25./[23] Technical Release No. 25 contains allowable design velocities developed by both the USSR/[27] and by Fortier and Scobey./[9] These allowable design velocities are related to soil grain size and have been proven over long periods of successful channel design. The major emphasis has been placed on non-cohesive soils. Only limited allowable-channel-velocity criteria for cohesive soils are available.

Technical Release No. 25 also presents the latest tractive force design analyses organized by Lane/[16] in 1955. Further attempts to define allowable tractive forces for cohesive materials have recently been made. The most recent Technical Release No. 25 design manual, edition dated 9 December 1968, attempts to relate unconfined compressive strength to allowable tractive power. (Tractive power is defined as the product of the allowable tractive force and velocity.) Based on discussions with Dr. George Kalkanis and others from the Soil Conservation Service, it is our understanding that some problems are still developing in cohesive channels despite attempts to relate erodibility to unconfined compressive strength. Problems are also occurring with slope stability.

United States Army Corps of Engineers - The Army Corps of Engineers in San Francisco has established allowable velocity criteria for design. Allowable velocities of 6 ft per second are used for coarse sands and gravel, and of 5 ft per second for fine sands and silts. If higher velocities are needed, the channels are always lined. Clay channels are, for the most part, also lined.

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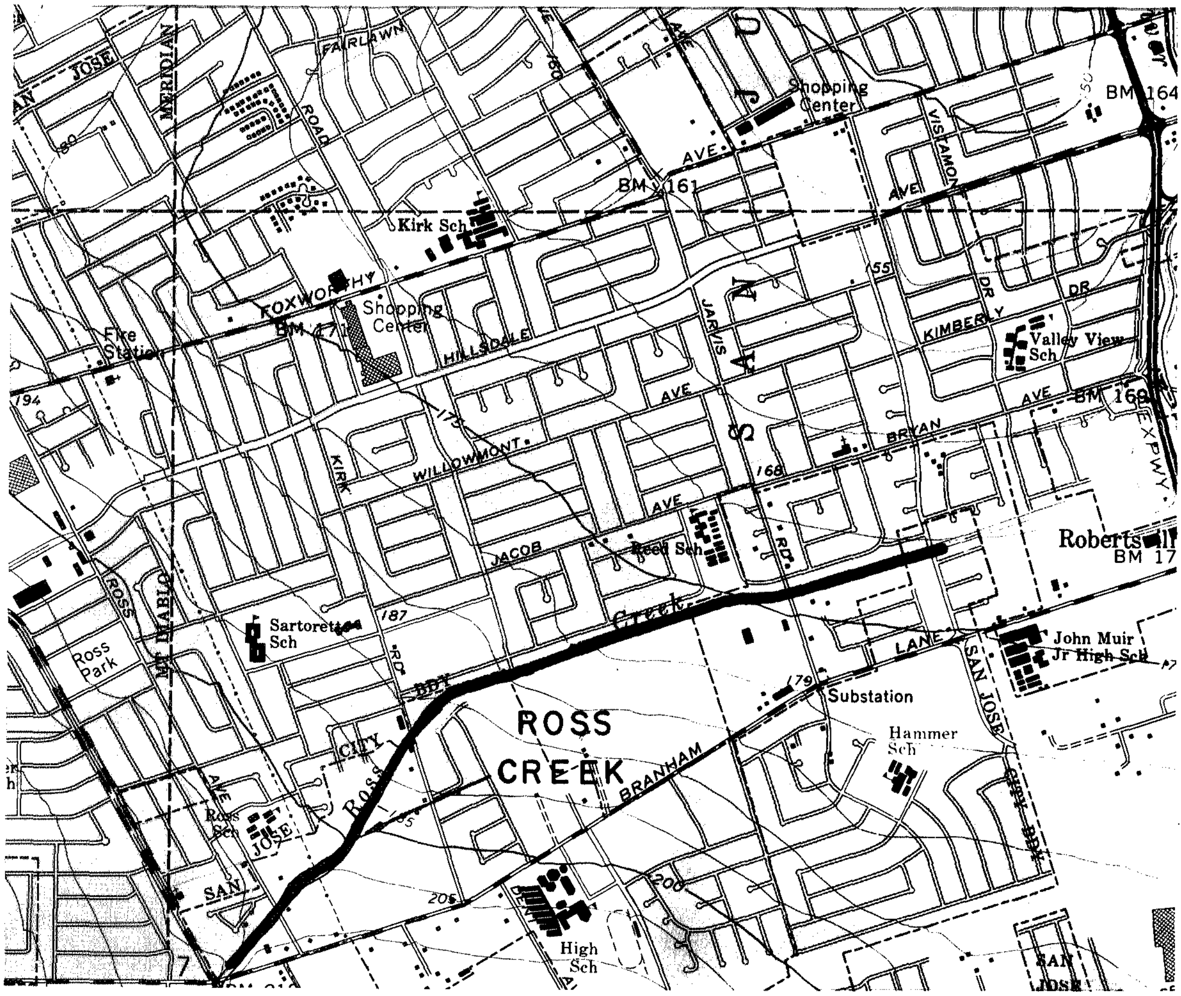
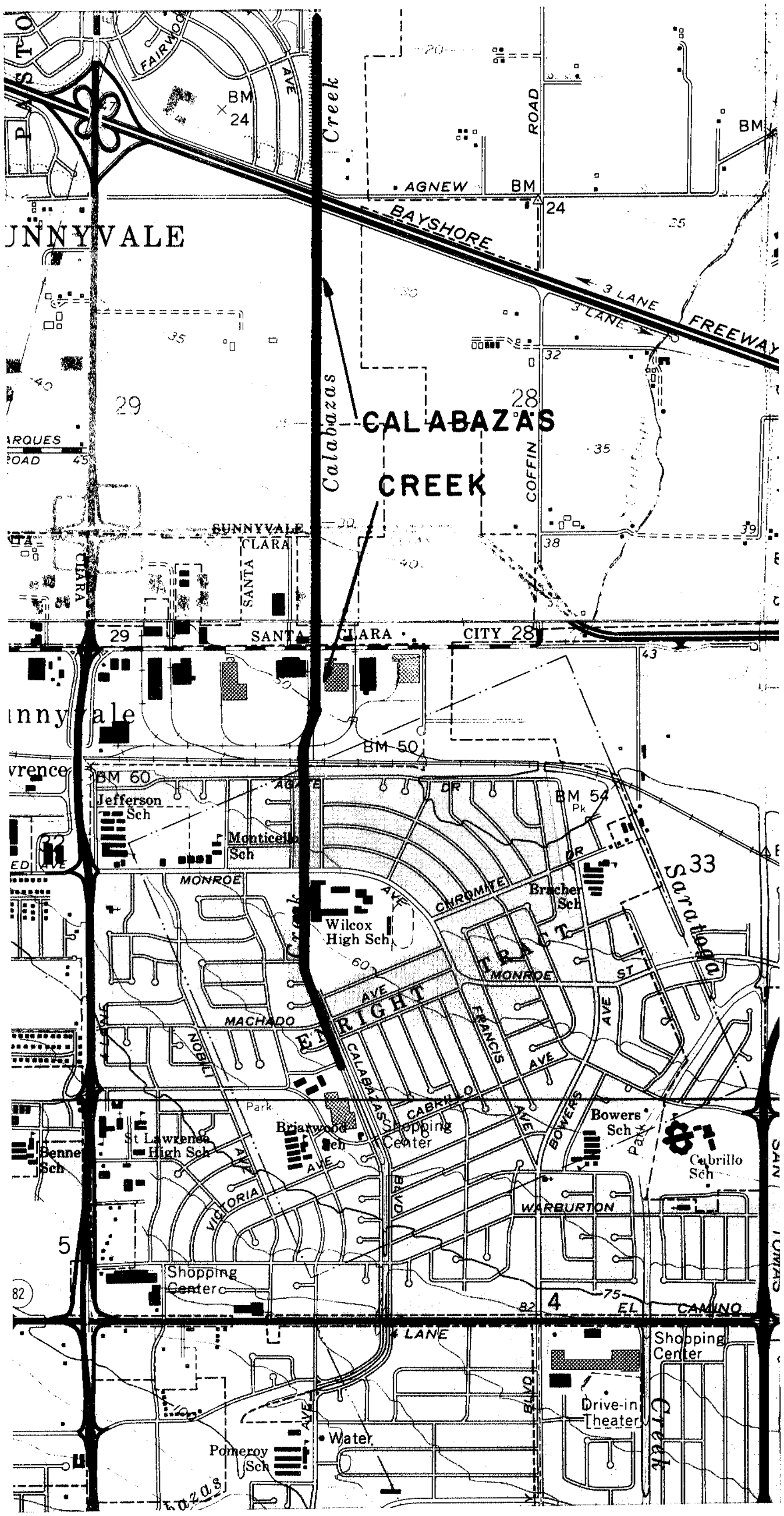


ROSS CREEK

LIMITS OF CHANNEL INSPECTION

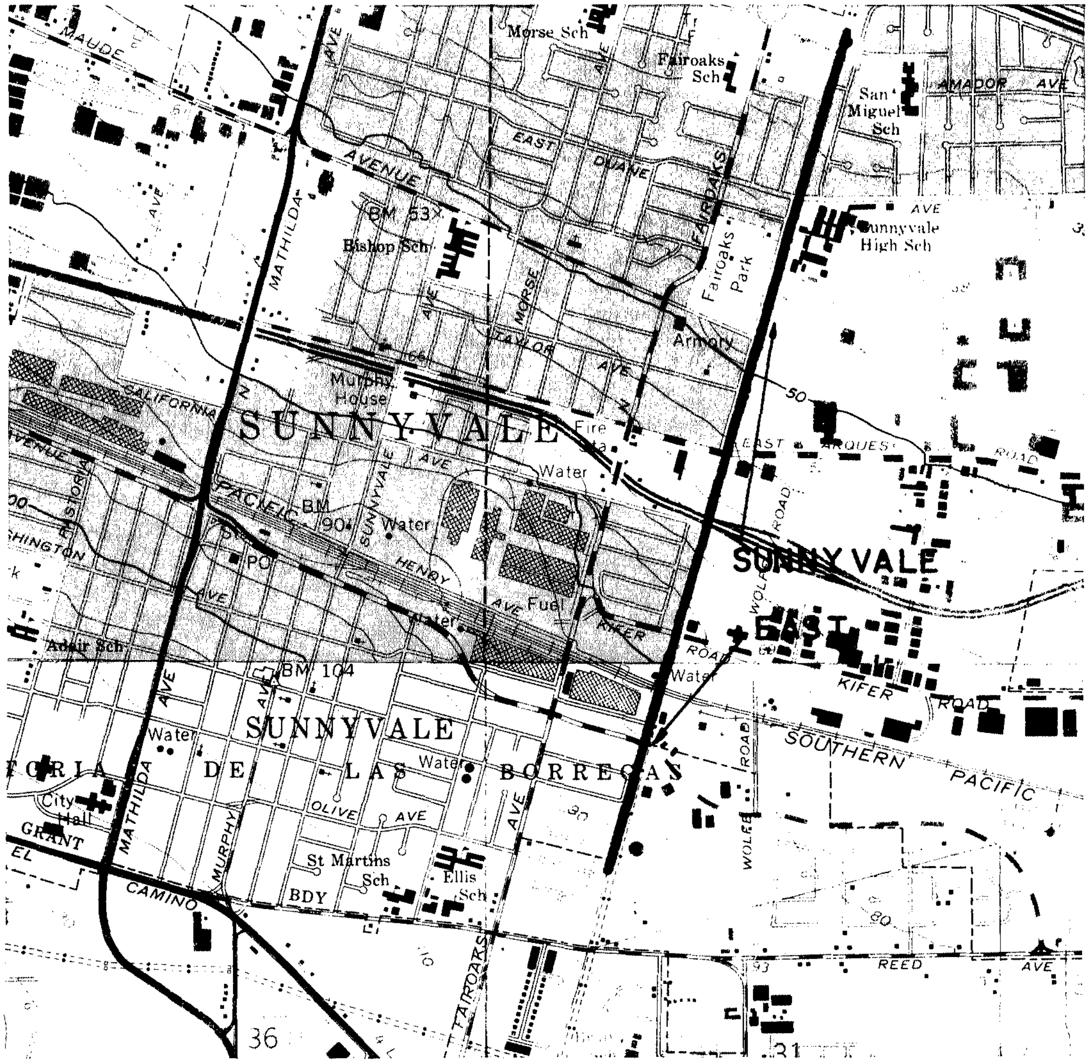
FIG. 1



CALABAZAS CREEK

LIMITS OF CHANNEL INSPECTION

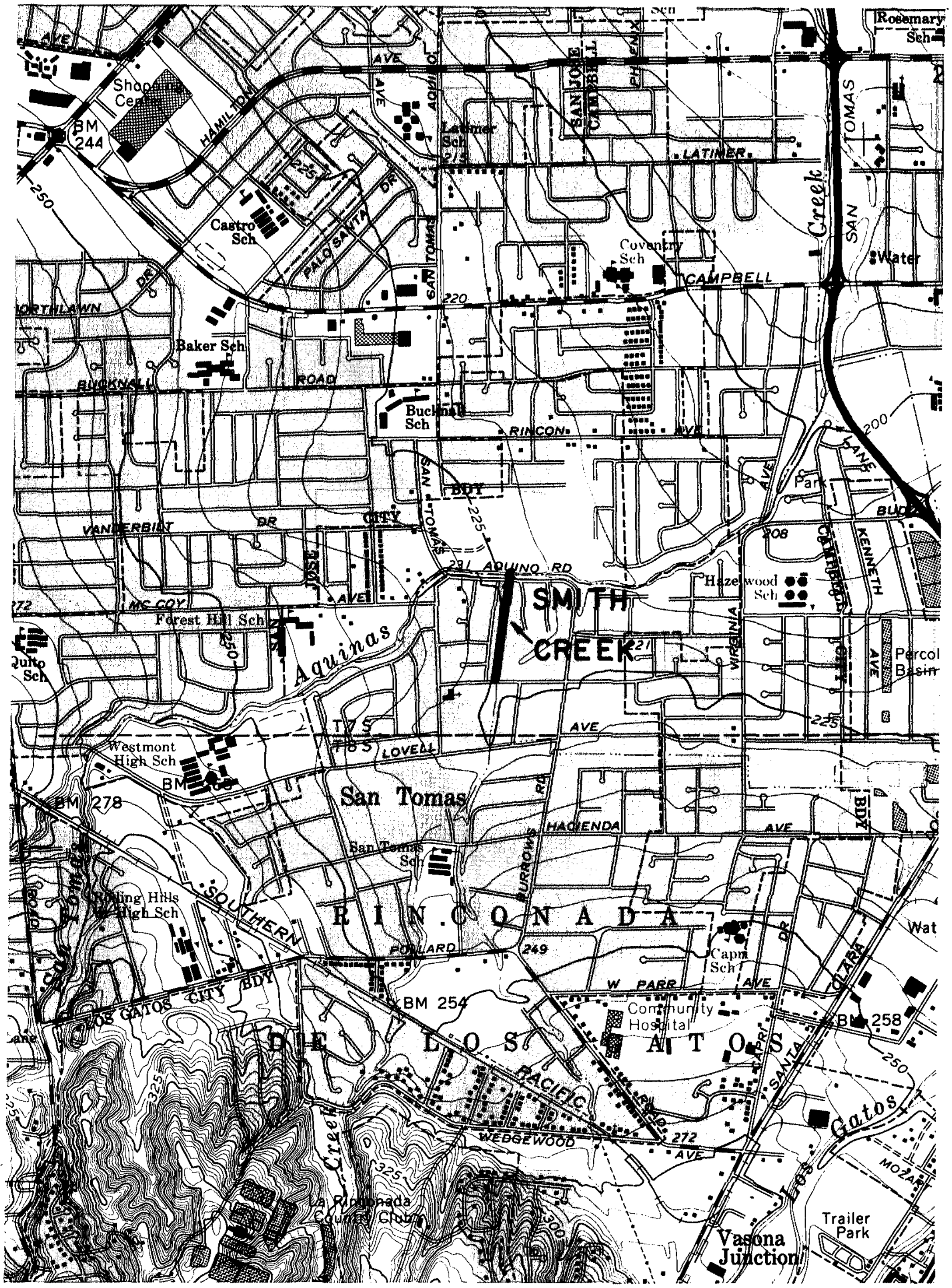
FIG. 2



SUNNYVALE EAST

LIMITS OF CHANNEL INSPECTION

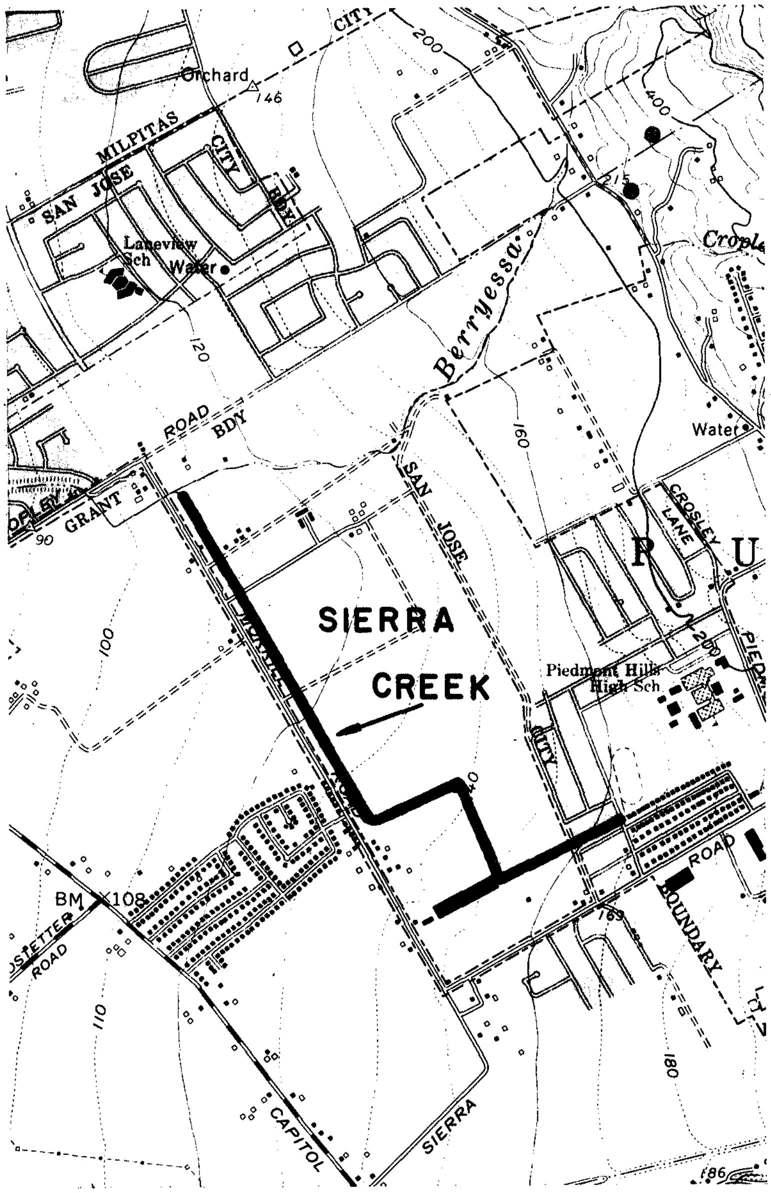
FIG. 3



SMITH CREEK

LIMITS OF CHANNEL INSPECTION

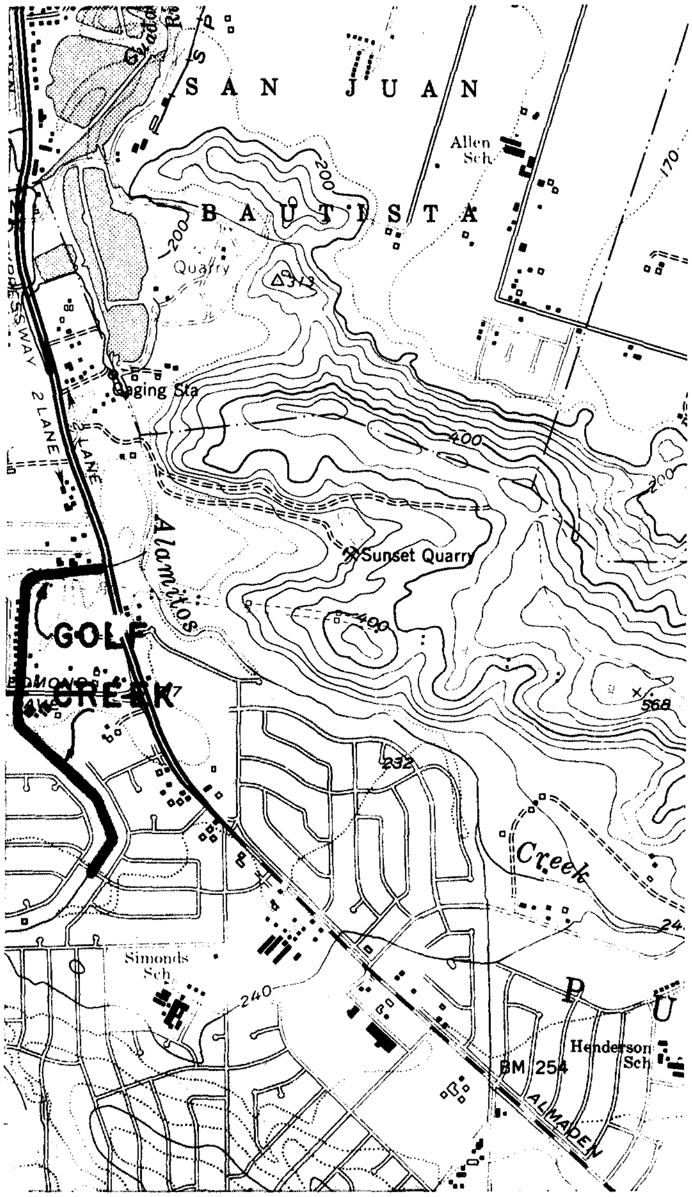
FIG. 4



SIERRA CREEK

LIMITS OF CHANNEL INSPECTION

FIG. 5



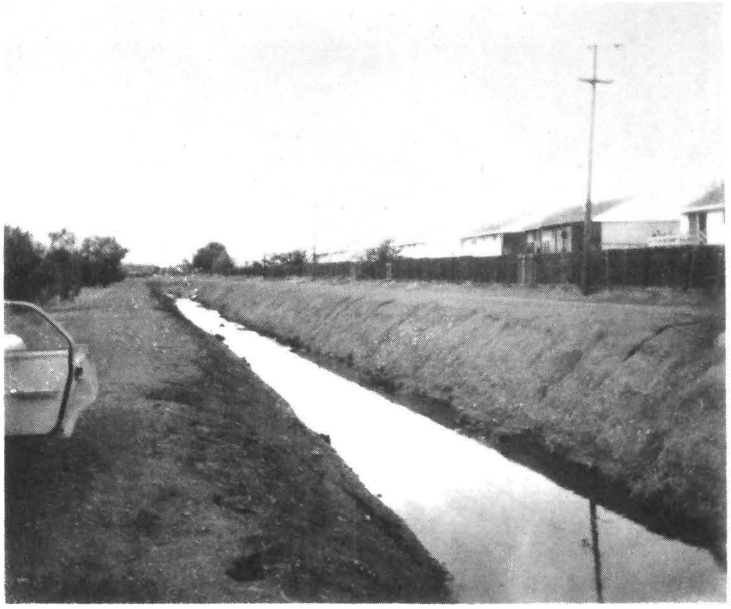
GOLF CREEK

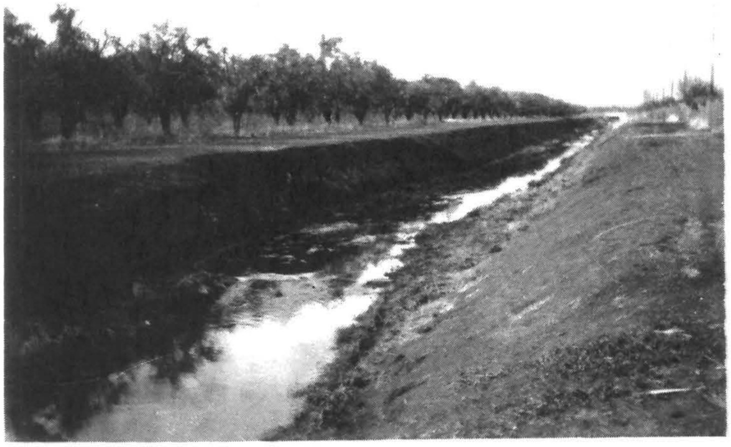
LIMITS OF CHANNEL INSPECTION

FIG. 6

ROSS CREEK at Meridian
San Jose

(Looking East or upstream)

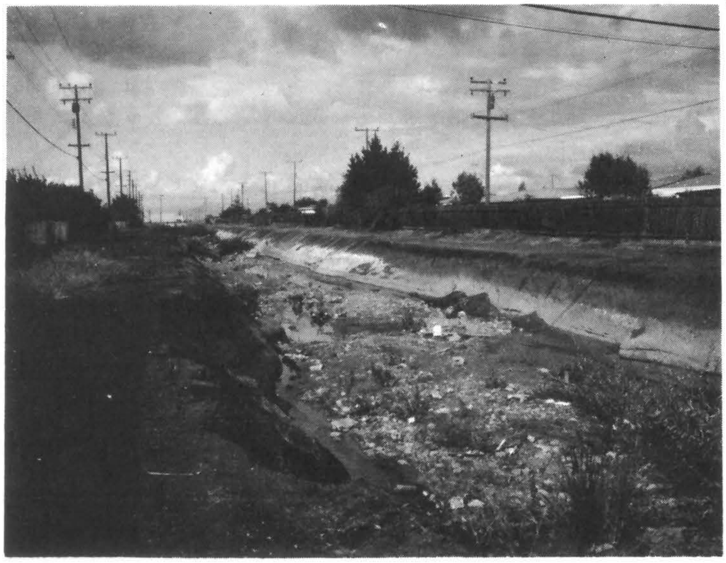




ROSS CREEK
1000 Ft. West of Cherry St.

(Looking East or upstream)

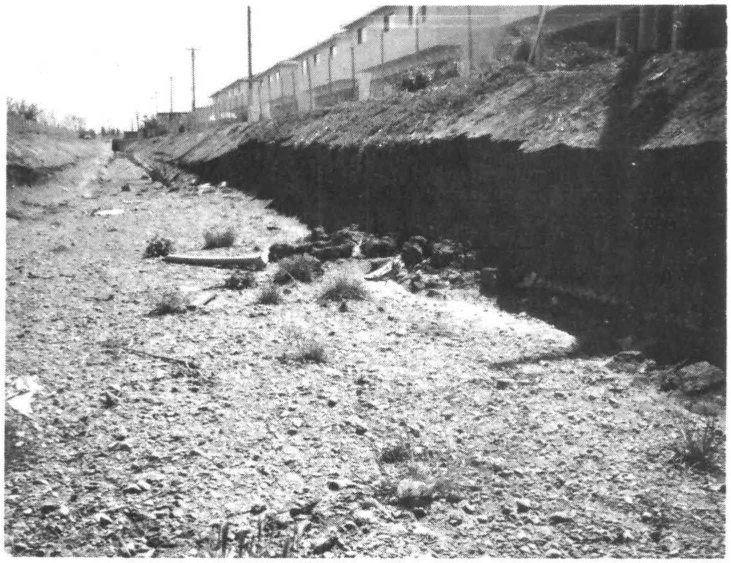
FIG. 7



CALABAZAS CREEK

Approx. 500 ft
North of Monroe St.

(Looking North or
downstream)

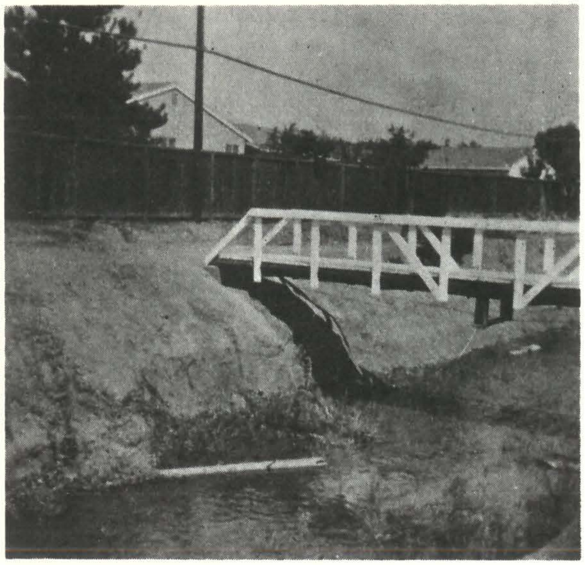


SUNNYVALE EAST CHANNEL

Approx. 1000 ft North
of Reed St.

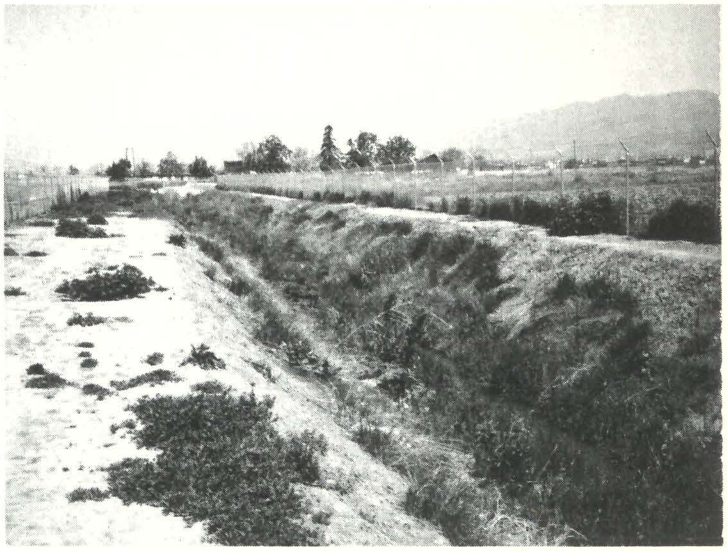
(Looking South or
upstream)

FIG. 8



SMITH CREEK
600 Ft North or Elam Ave.,
Campbell

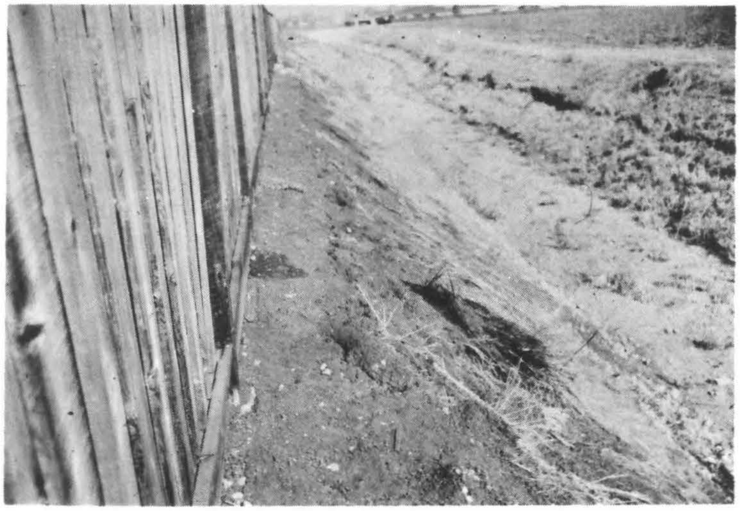
(Looking North or downstream)



SIERRA CREEK
1000 Ft South of
Berryessa Creek, San
Jose

(Looking North or
downstream)

FIG. 9



GOLF CREEK
At Redmond Avenue,
San Jose

(Looking North or
downstream)

FIG. 10

RECOMMENDED LIMITING TRACTIVE FORCES

FOR FLAT CHANNELS OF INFINITE WIDTH

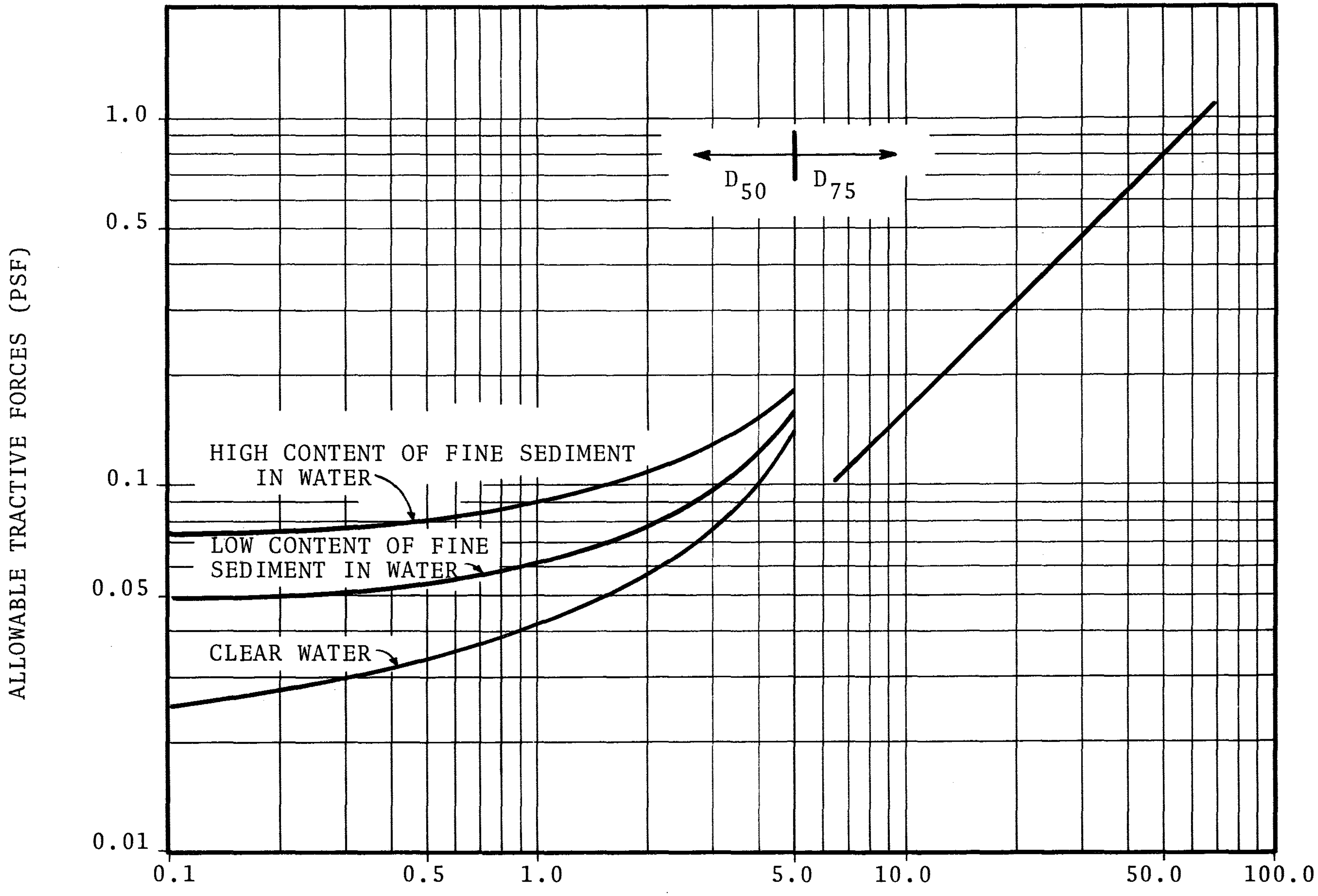
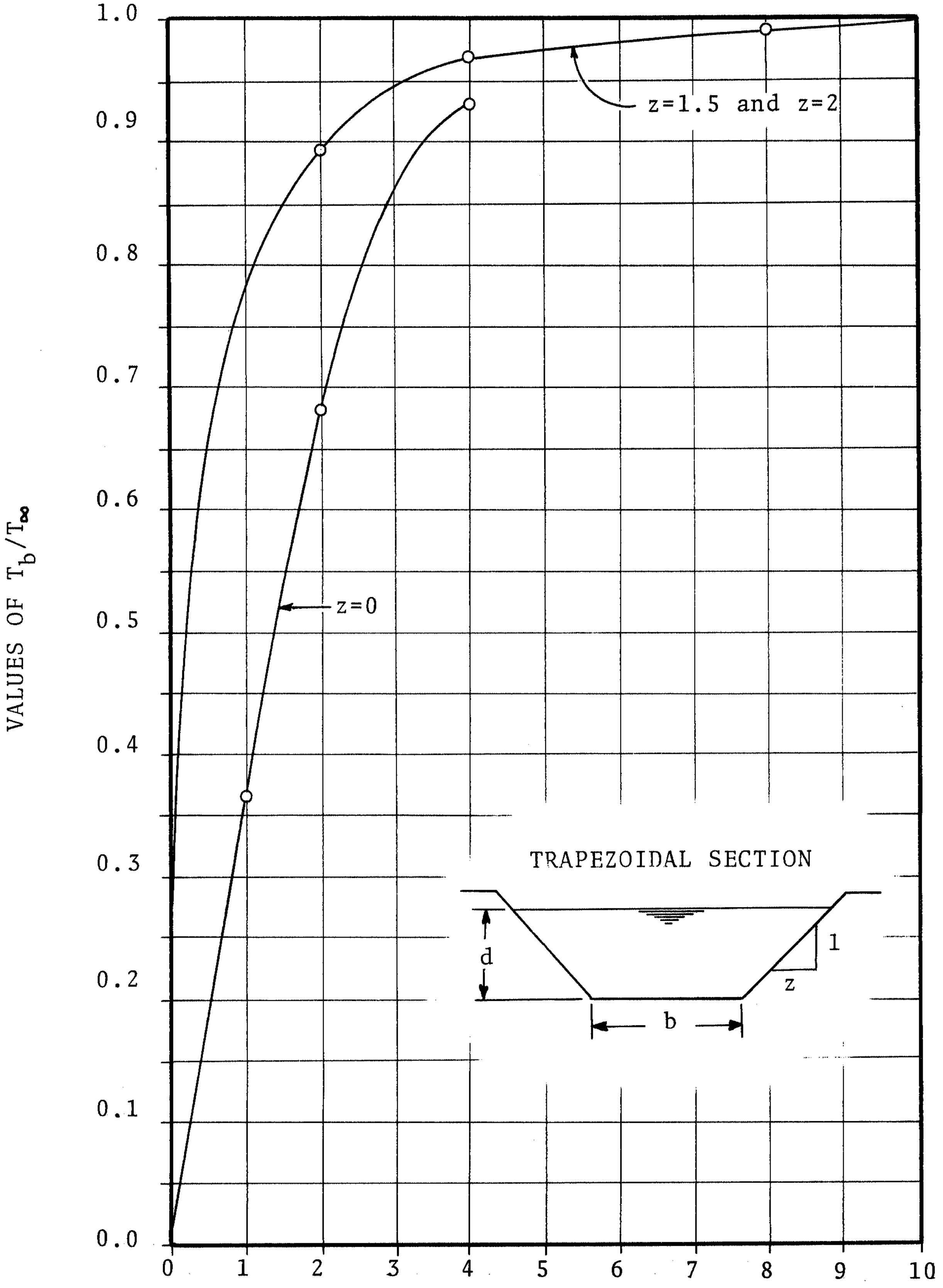


Fig. 11

After Lane/[17] (1955)

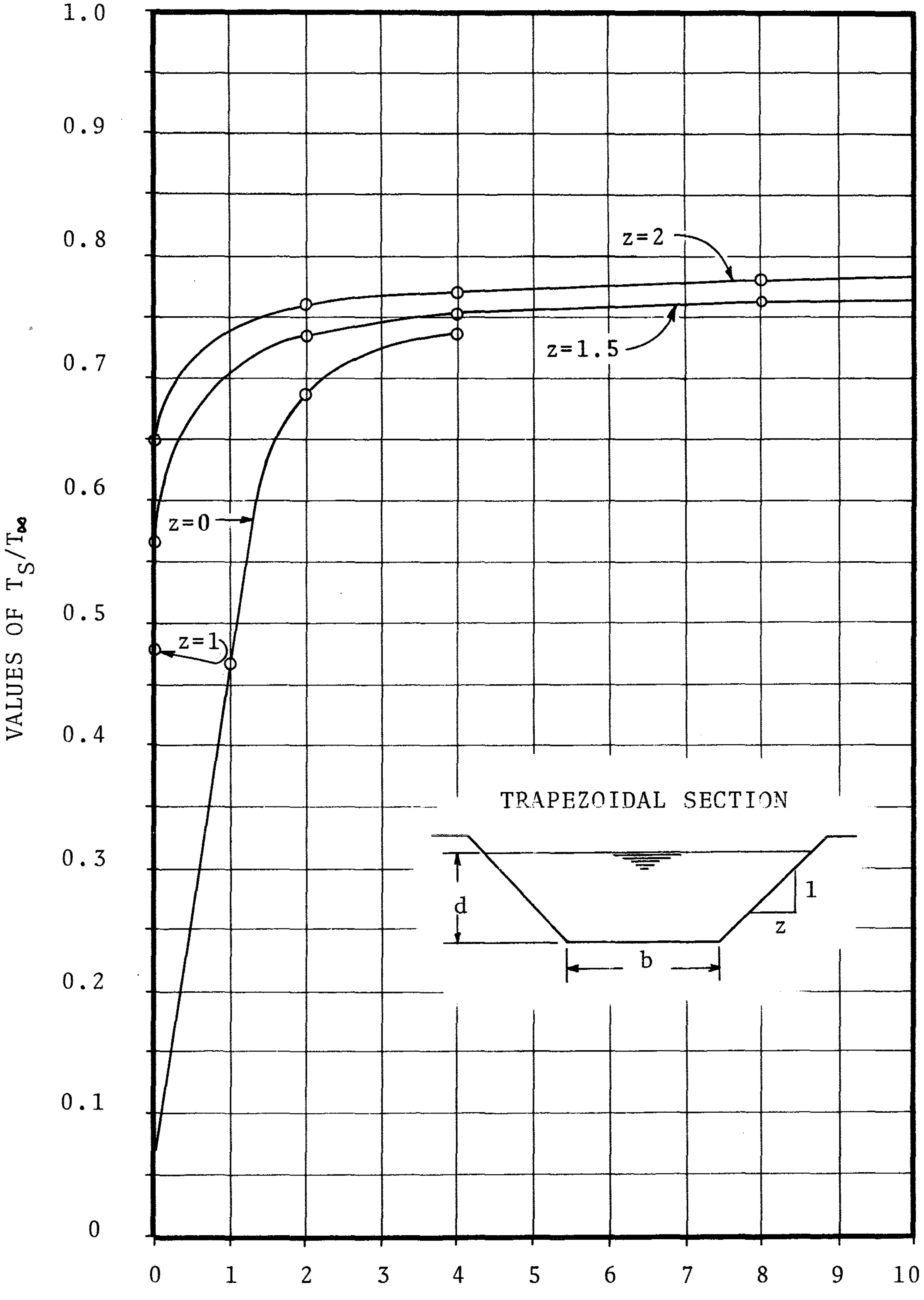
ACTUAL MAXIMUM TRACTIVE FORCE (T_b)
ON BED OF STRAIGHT TRAPEZOIDAL CHANNELS



Reference: U.S. Dept. of Agriculture
Soil Conservation Service
Technical Release #25 /24

Fig. 12

ACTUAL MAXIMUM TRACTIVE FORCES (T_S) ON SIDES OF STRAIGHT TRAPEZOIDAL CHANNELS



Reference: U.S. Dept. of Agriculture
Soil Conservation Service
Technical Release #25/24

FIG. 13

ALLOWABLE TRACTIVE FORCE
VERSUS PLASTICITY INDEX

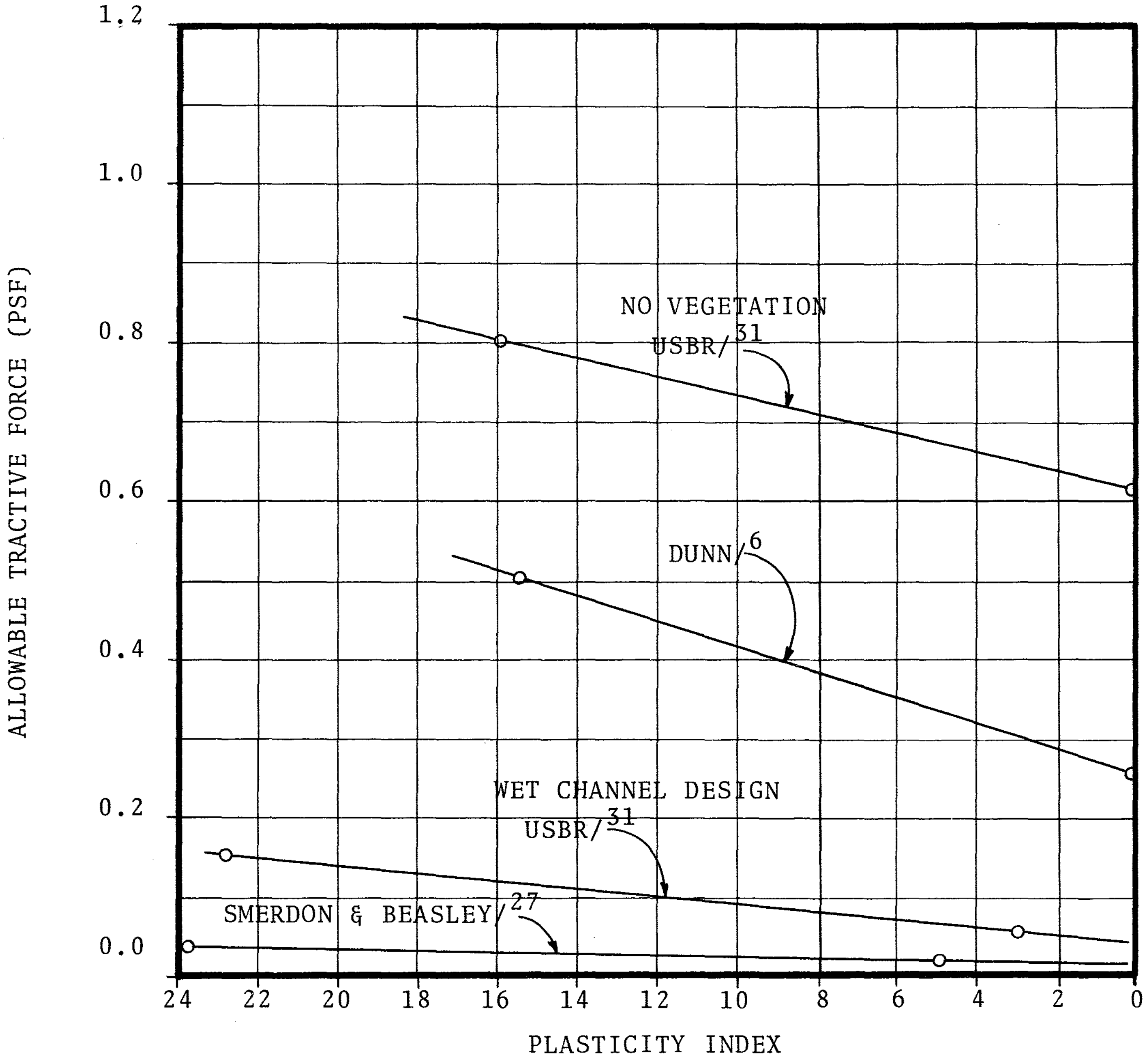


Fig. 14

ALLOWABLE TRACTIVE FORCES VS. SOIL GRAIN SIZE

(BY WOODWARD-LUNDGREN & ASSOCIATES)

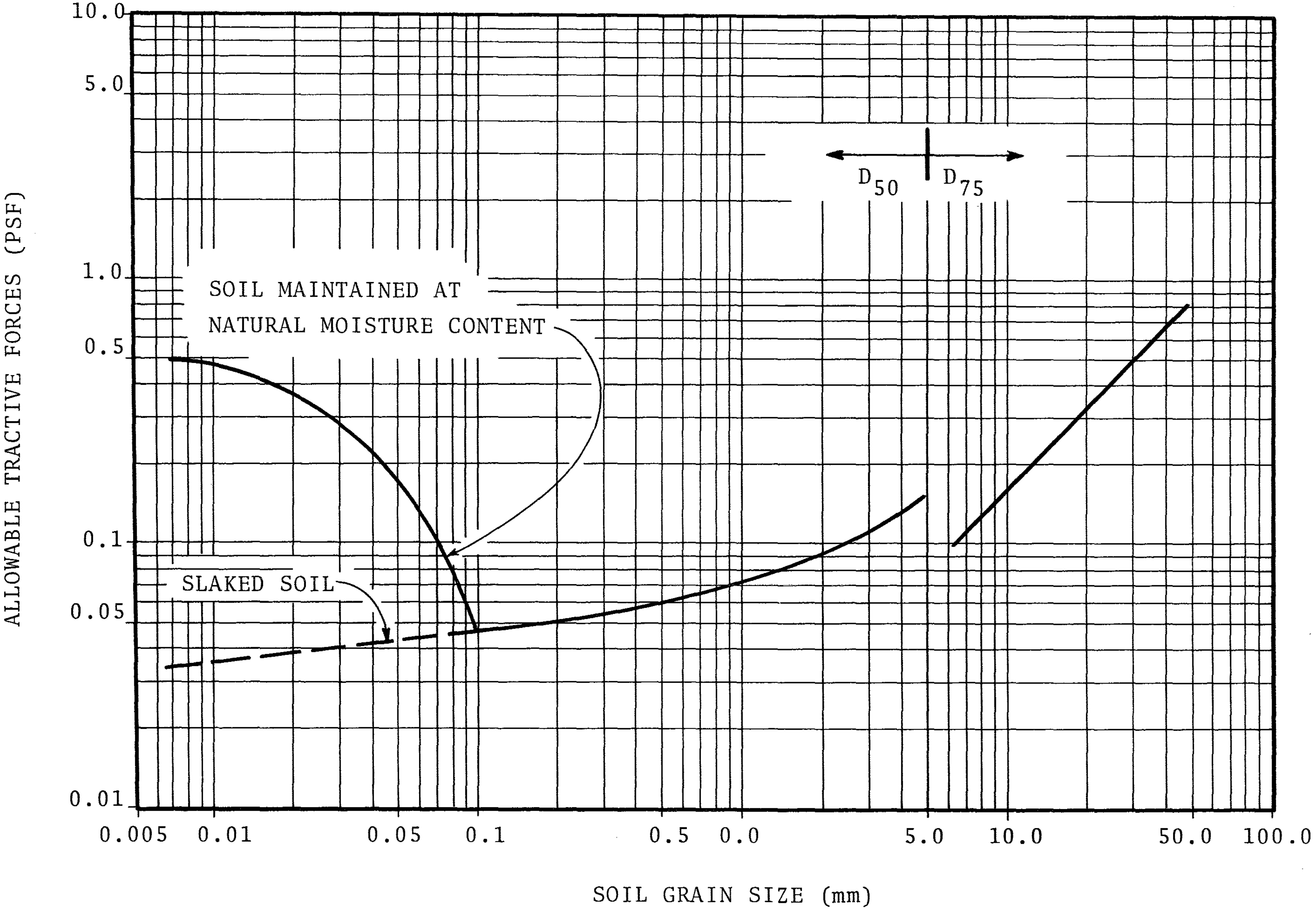


Fig. 15

ROSS CREEK

PROJECT:

MECHANICAL ANALYSIS CURVES

SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
#1 —— #3 —·—·— #4 - - - -									

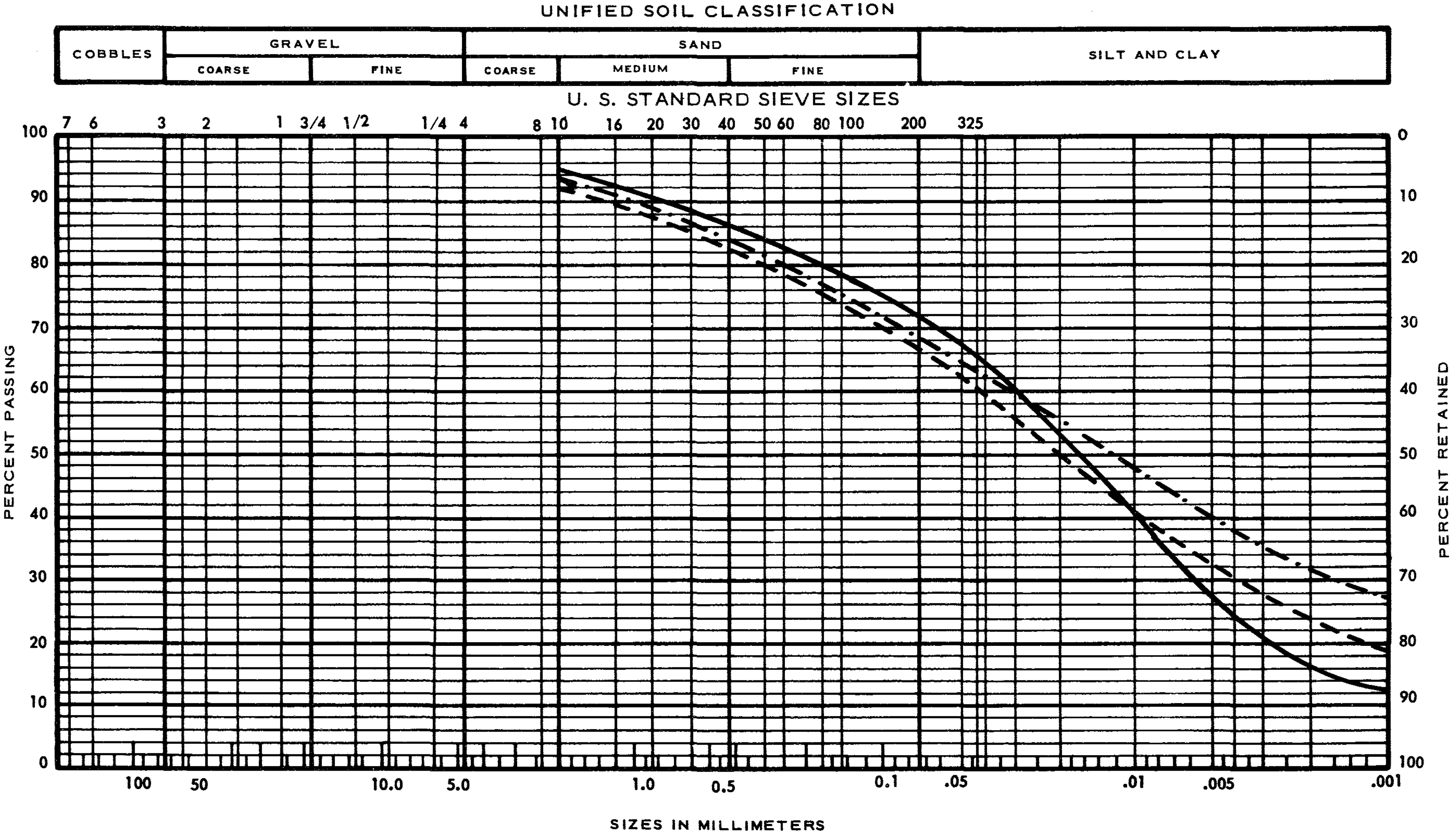


FIG. 16

ROSS CREEK

PROJECT: Erosion Study	MECHANICAL ANALYSIS CURVES								
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
Ross Creek #2									

UNIFIED SOIL CLASSIFICATION

COBBLES	GRAVEL		SAND			SILT AND CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

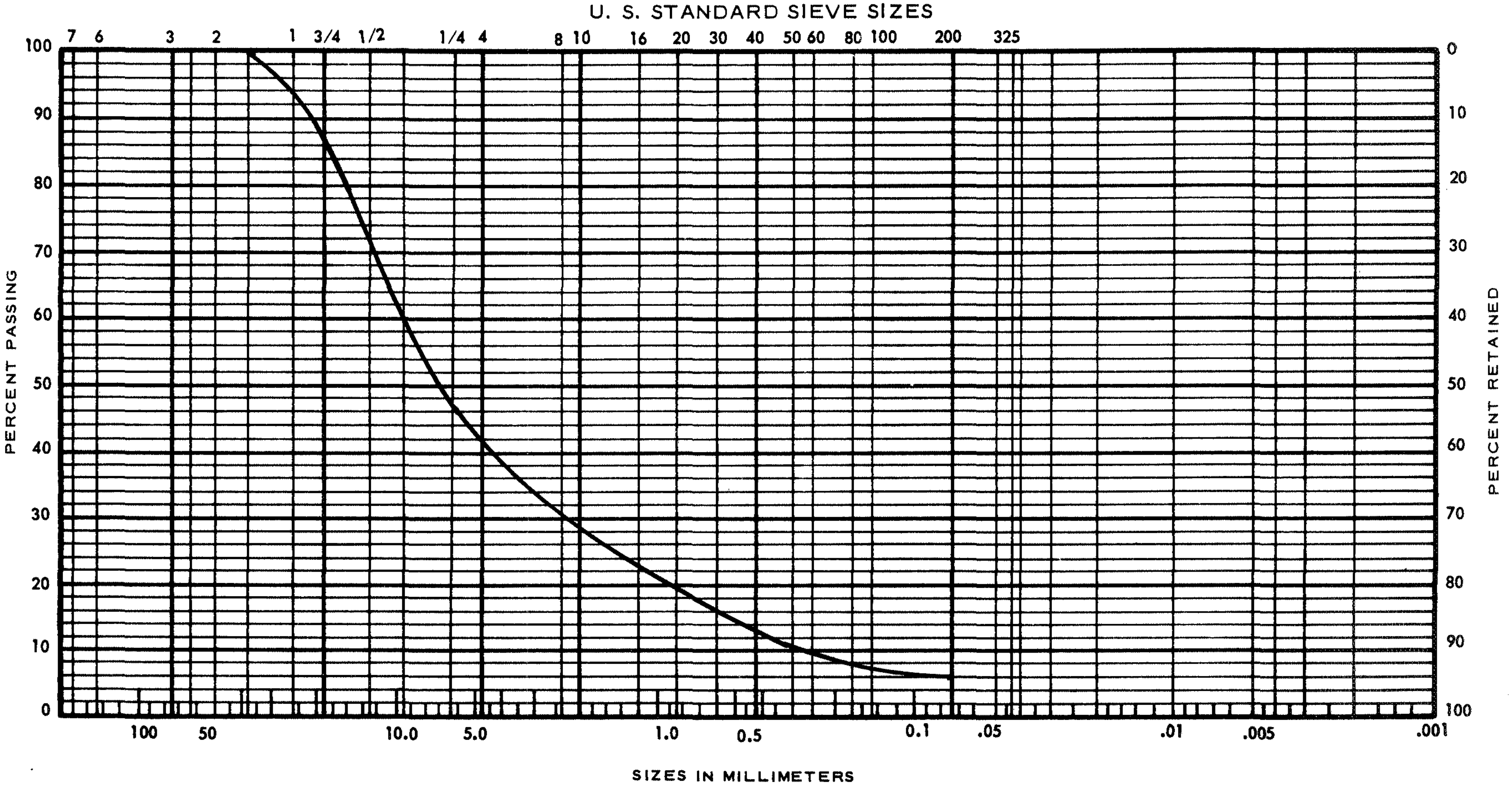


FIG. 17

CALABAZAS

PROJECT:	MECHANICAL ANALYSIS CURVES								
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
1-1 - - - -		32	15						
1-3 ———									

UNIFIED SOIL CLASSIFICATION

COBBLES	GRAVEL		SAND			SILT AND CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

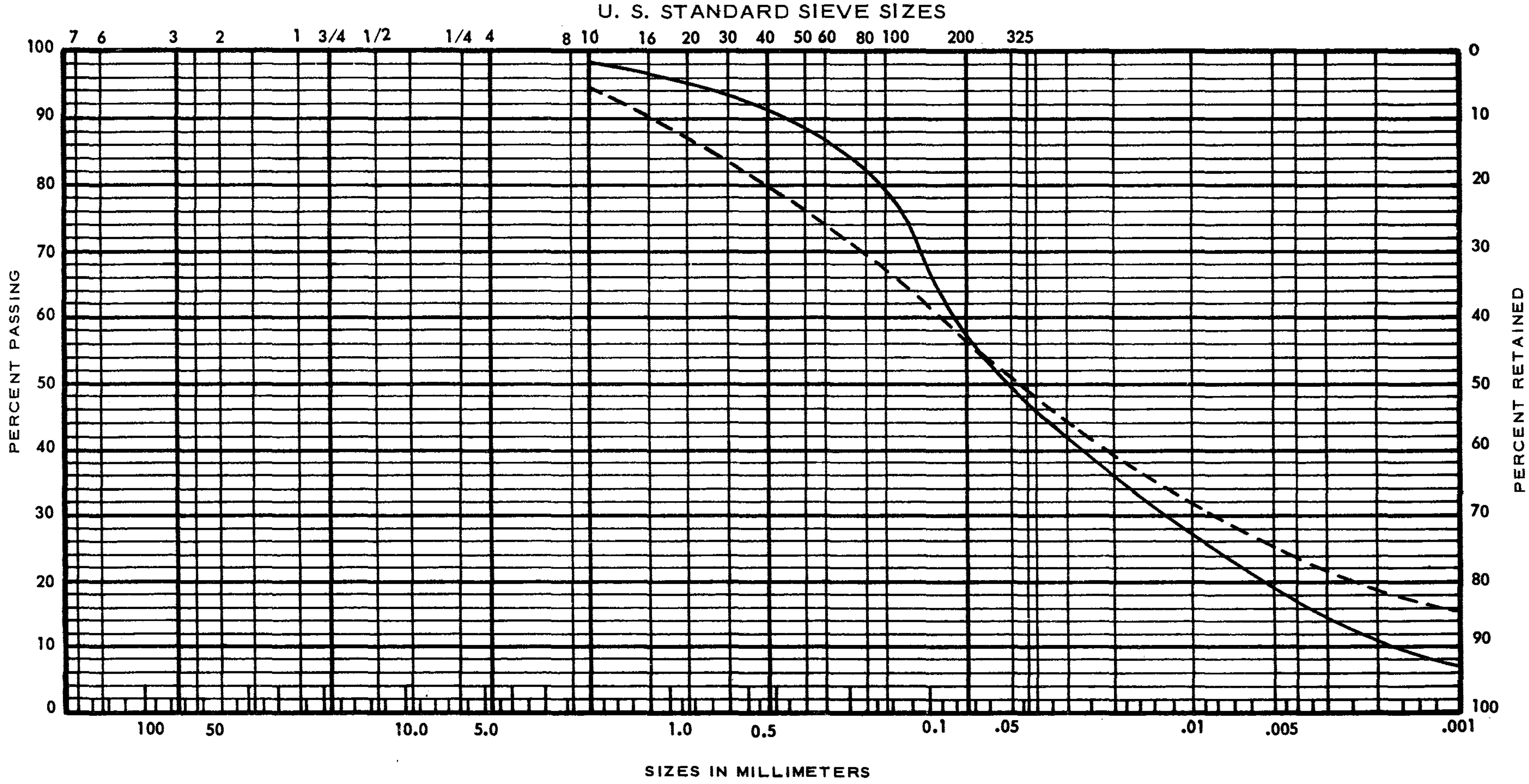


FIG. 18

CALABAZAS

PROJECT:	MECHANICAL ANALYSIS CURVES								
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
2-1		36	18						

UNIFIED SOIL CLASSIFICATION

COBBLES	GRAVEL		SAND			SILT AND CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

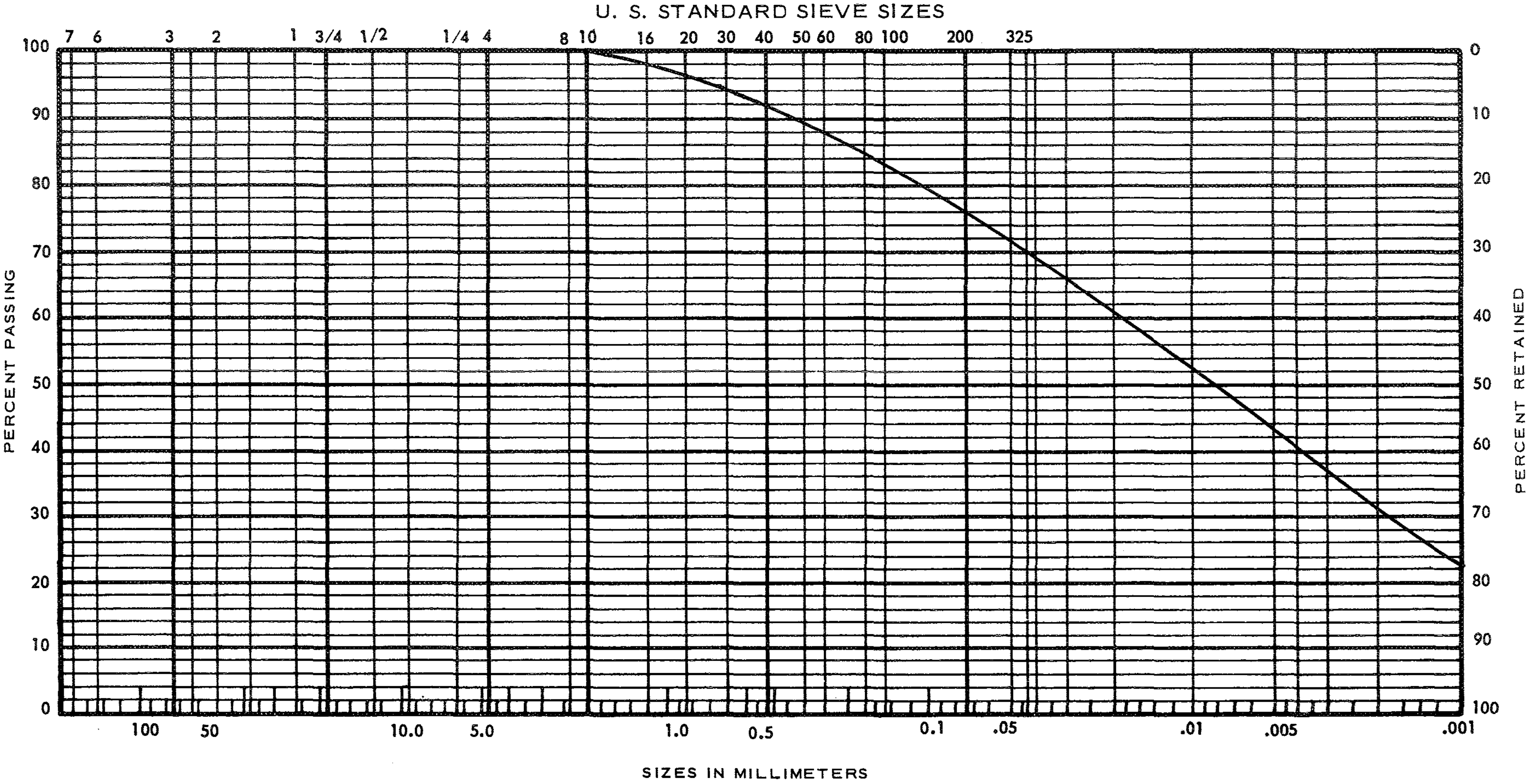


FIG. 19

CALABAZAS

PROJECT:	MECHANICAL ANALYSIS CURVES								
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
3-1 - - - -		39	23						
3-2 ———		43	26						

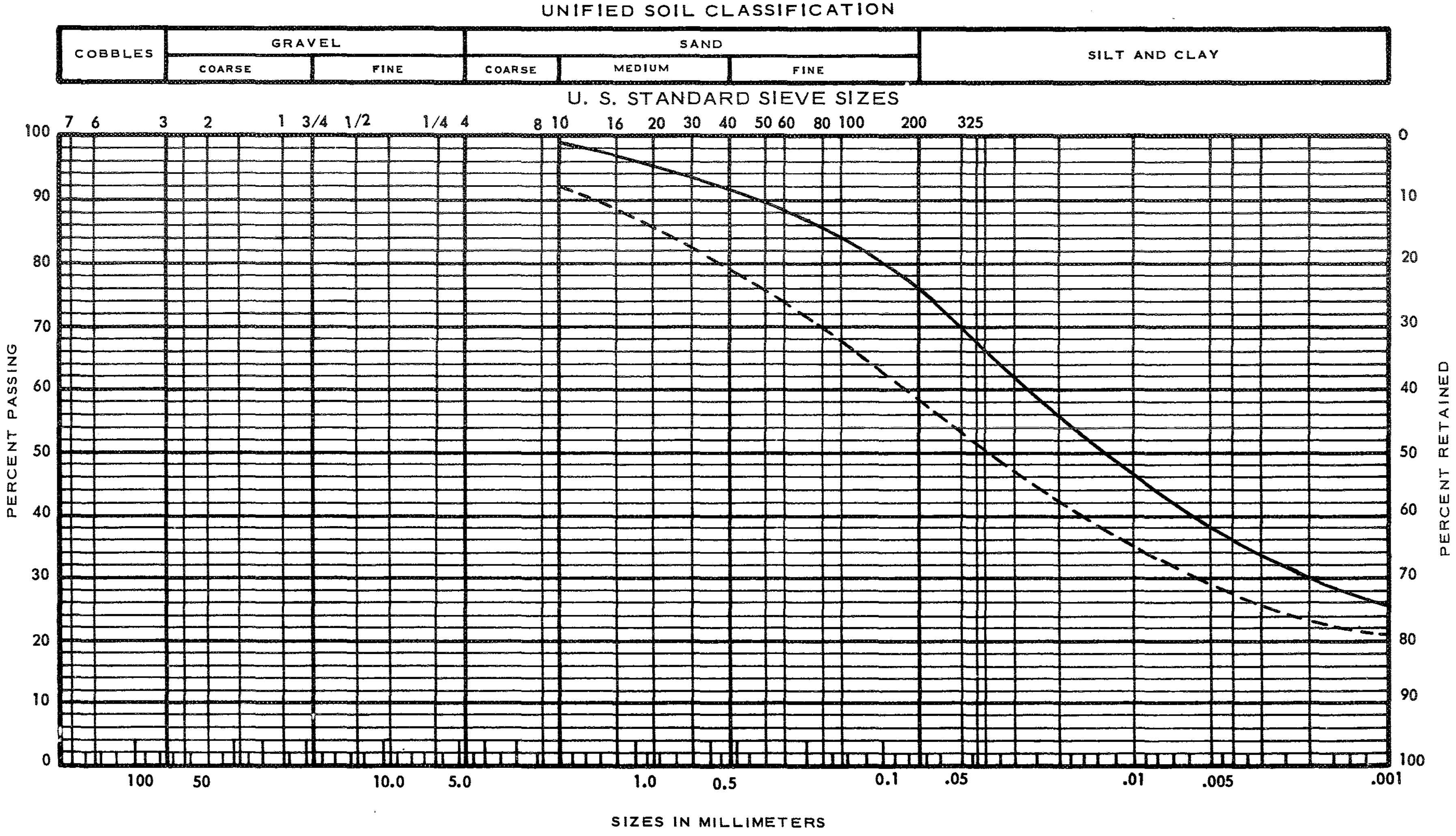


FIG. 20

CALABAZAS

PROJECT:	MECHANICAL ANALYSIS CURVES

SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
4-1 - - - -		37	20						
4-2 ——		39	20						

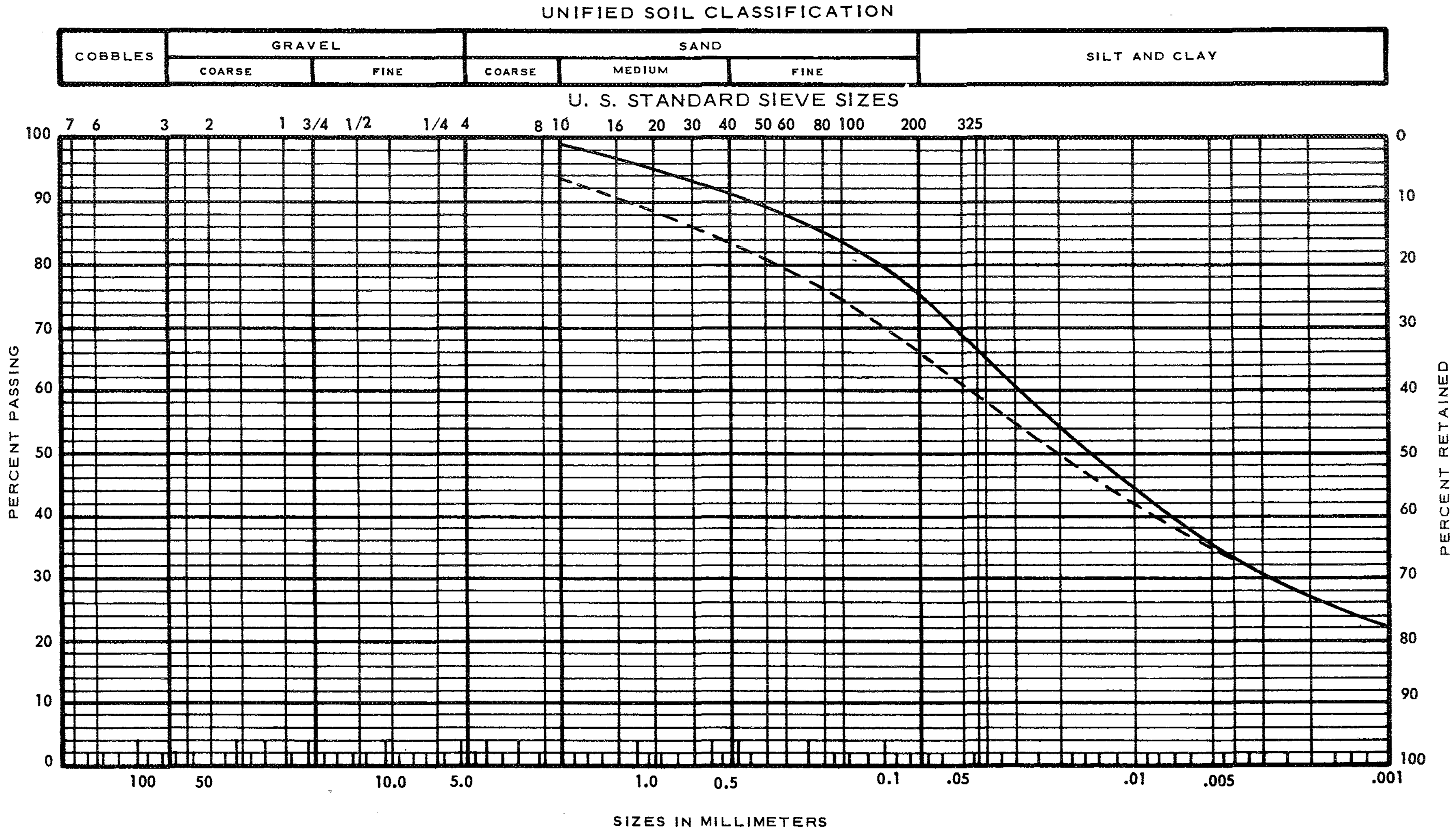


FIG. 21

CALABAZAS CREEK

PROJECT:				MECHANICAL ANALYSIS CURVES					
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
Calabazas 5-1 ——— 7-2 - - - -									

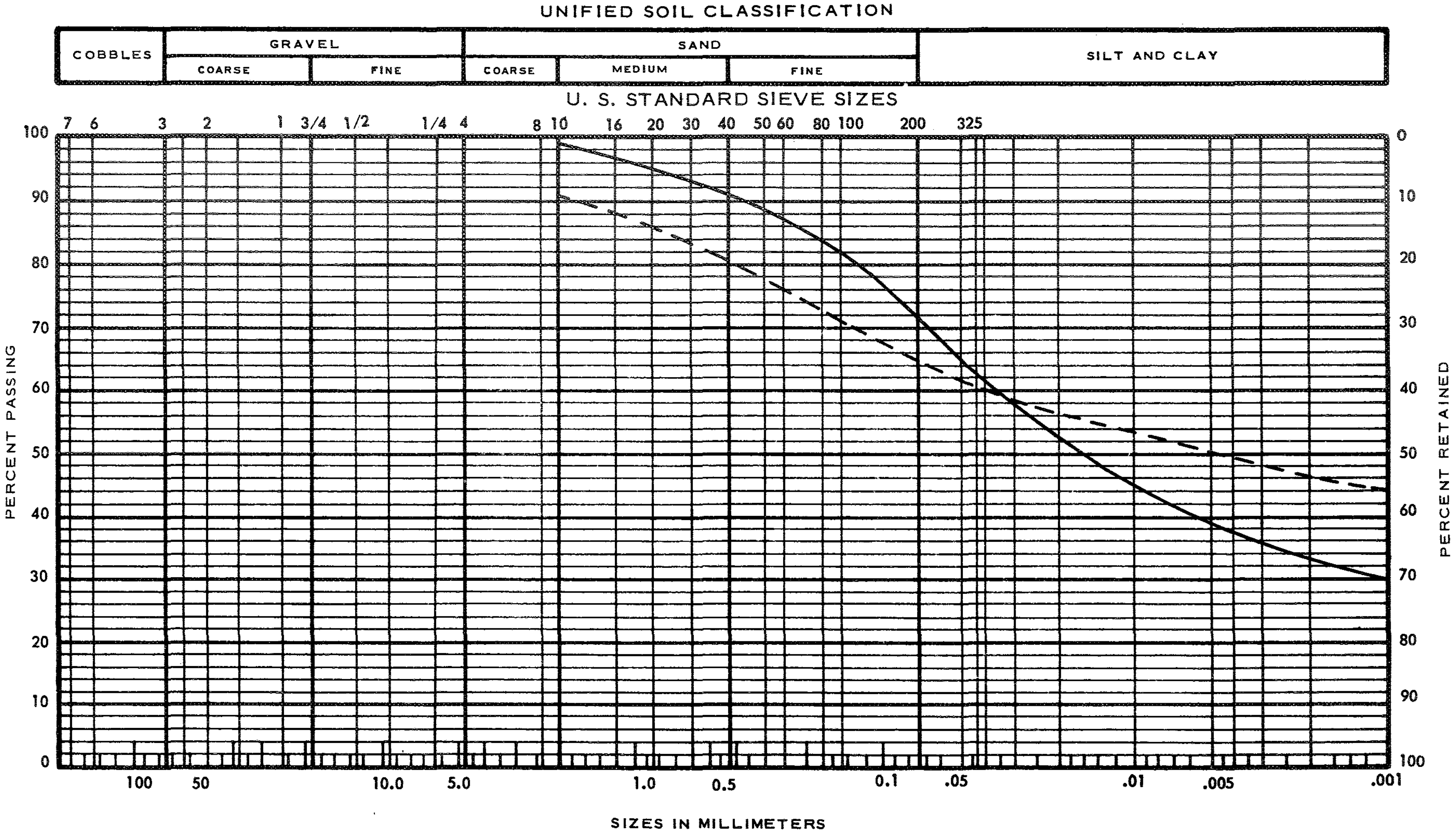


FIG. 22

SMITH CREEK

PROJECT: Erosion Study	**MECHANICAL ANALYSIS CURVES**

SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
Smith 3-1									

UNIFIED SOIL CLASSIFICATION

COBBLES	GRAVEL		SAND			SILT AND CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

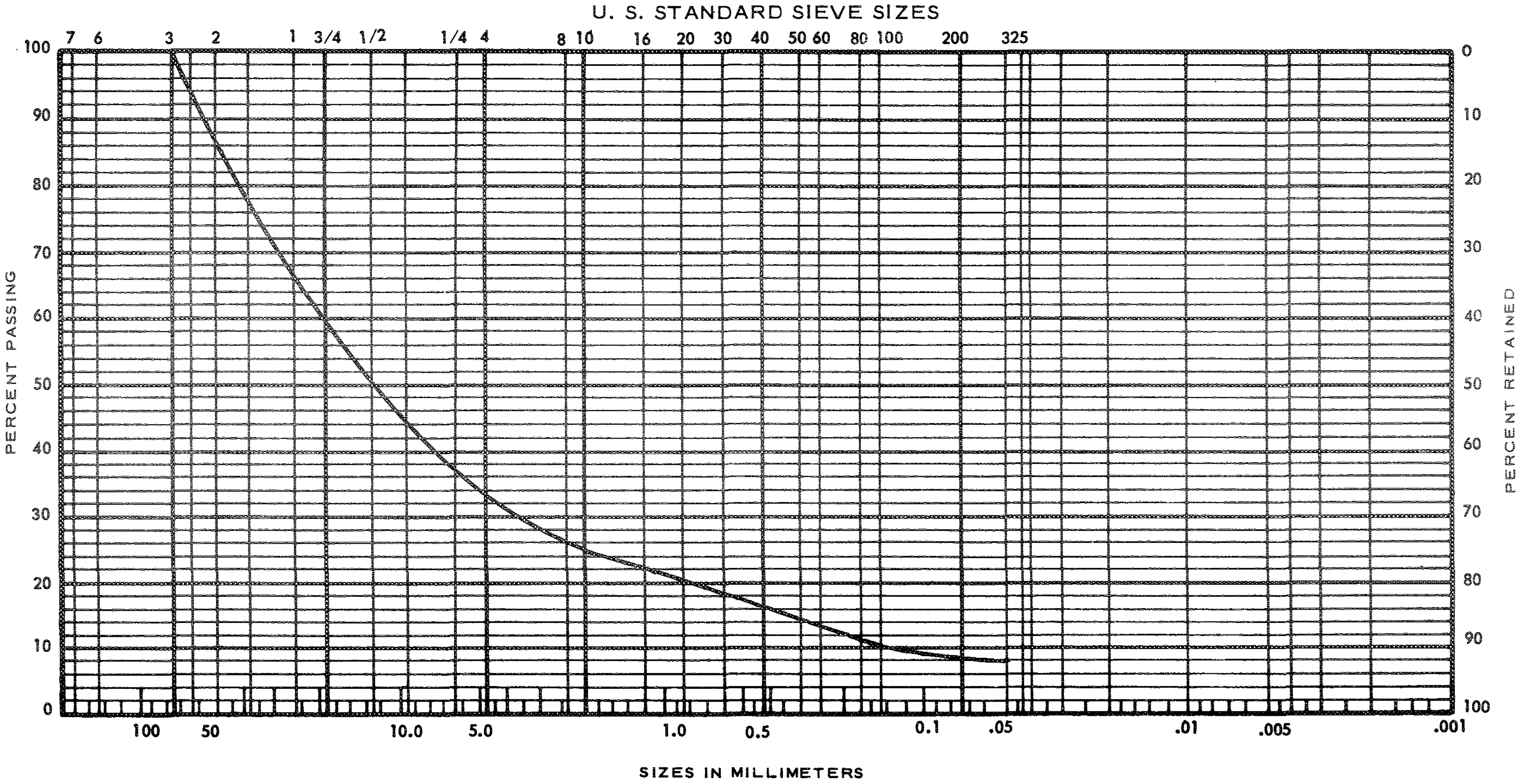


FIG. 23

SMITH CREEK

PROJECT:	MECHANICAL ANALYSIS CURVES

SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
3-2 - - -									
4-1 ——		37	18						

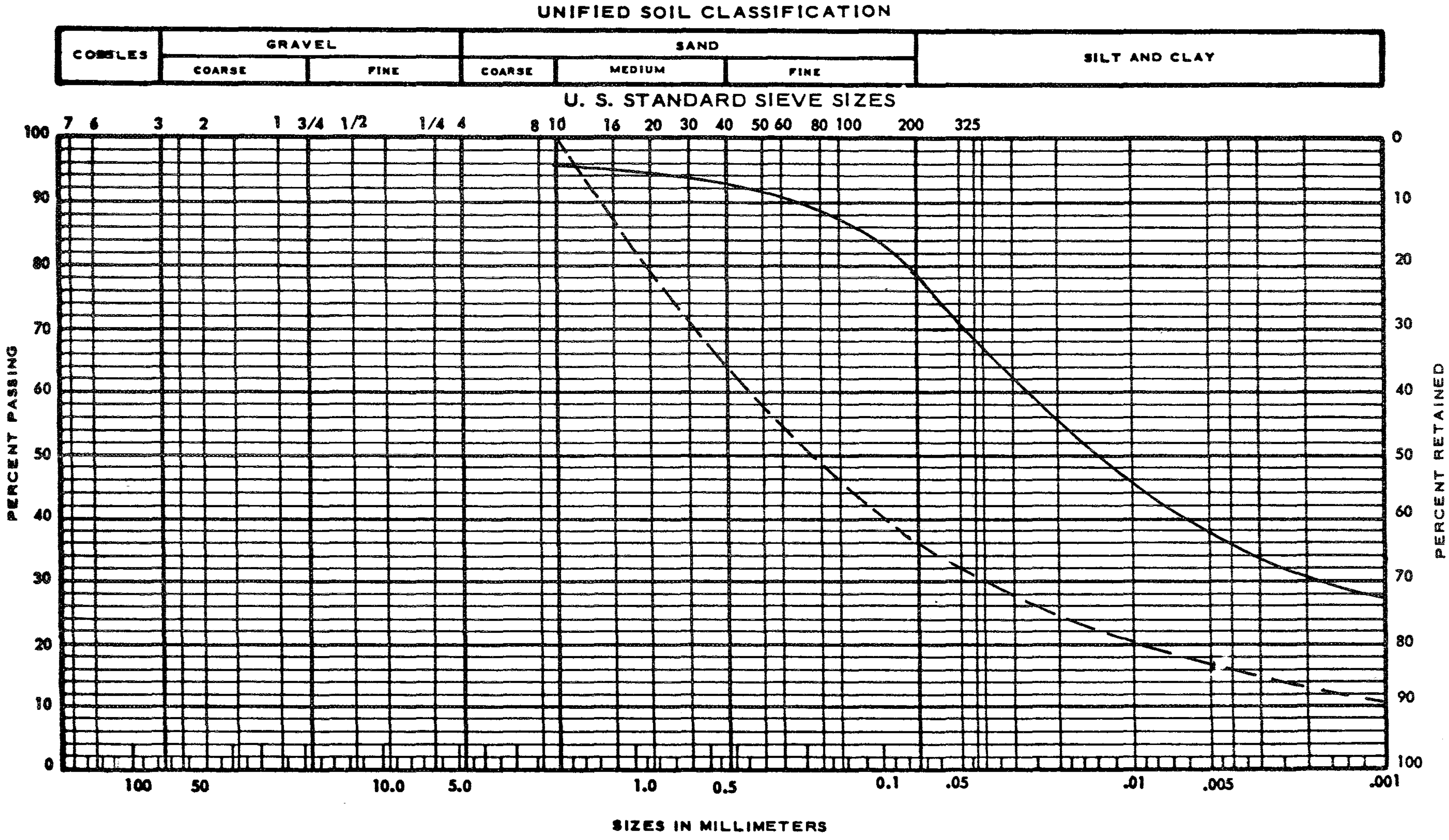


FIG. 24

SIERRA CREEK

PROJECT:				MECHANICAL ANALYSIS CURVES				
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
1-1 - - - -		38	20						
2 ———		36	12						
4-2 —·—·—		-	-						

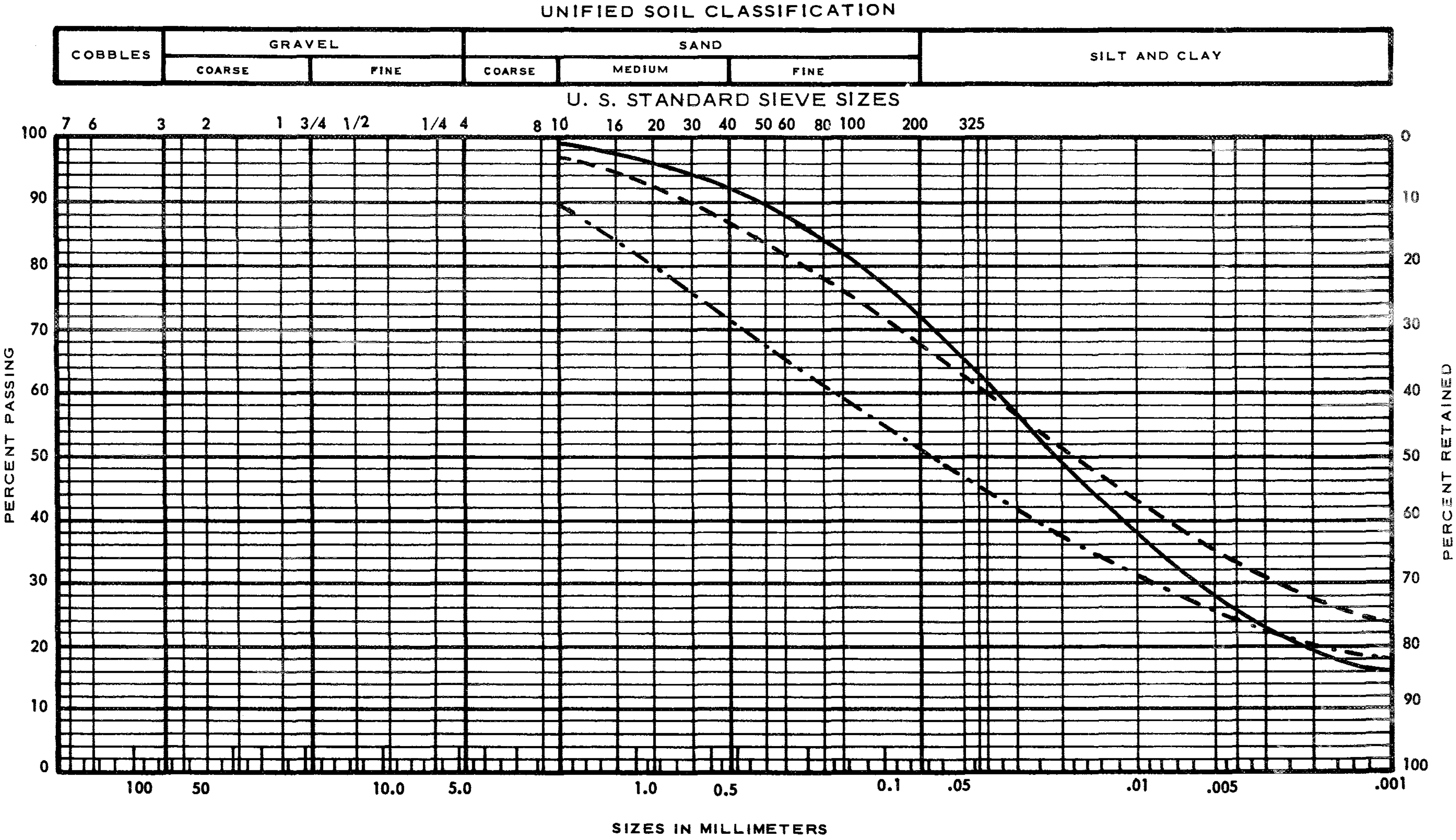


FIG. 25

SIERRA CREEK

PROJECT: Erosion Study	MECHANICAL ANALYSIS CURVES								
SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION	SAMPLE NO.	DEPTH	LL	PI	CLASSIFICATION
Sierra Creek #3									

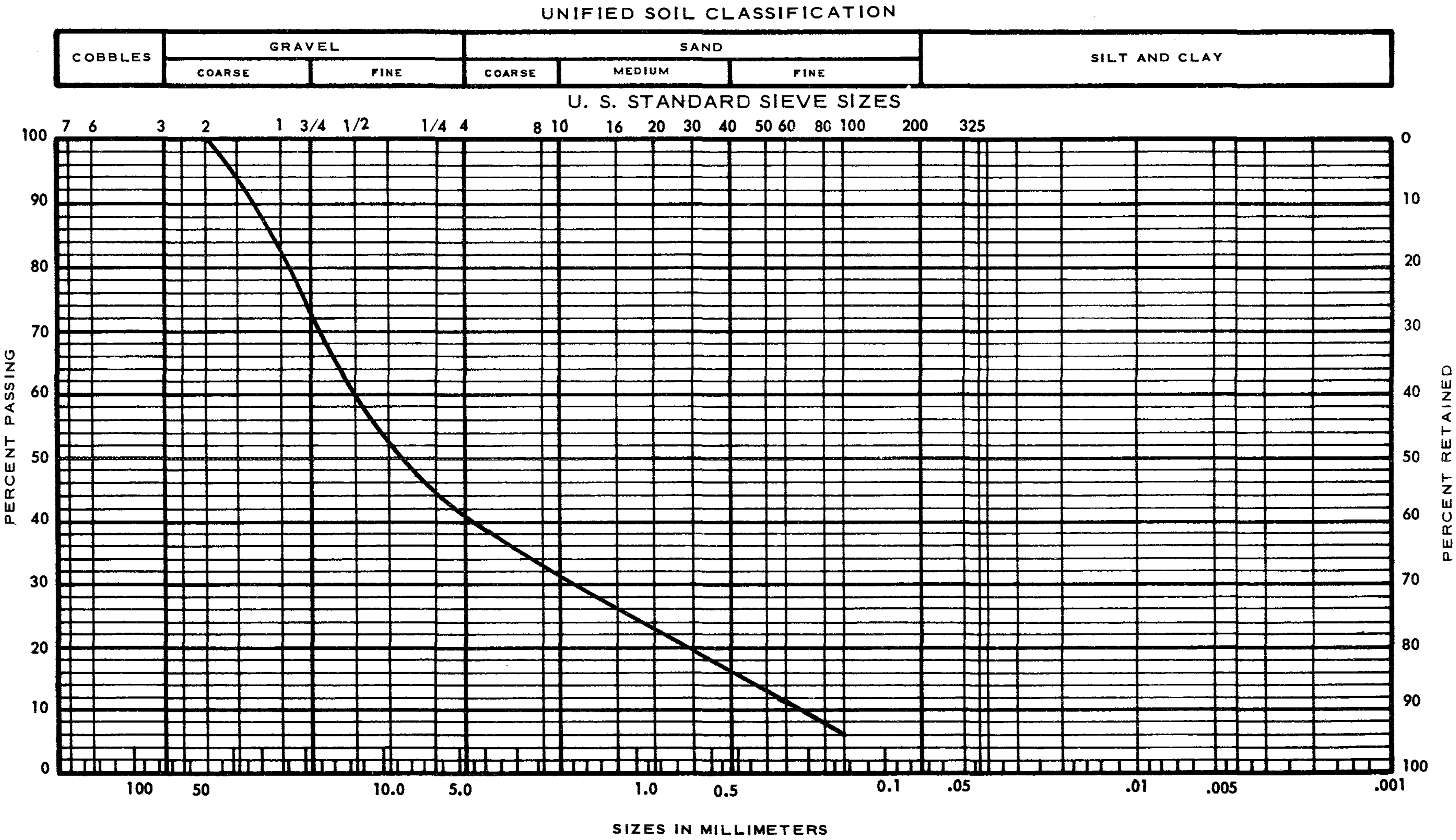


FIG. 26

TABLE I

SOIL CLASSIFICATIONS & LABORATORY TESTS

LOCATION & SAMPLE NO.		LOCATION	DEPTH ** (ft.)	CLASSIFICATION	LIQUID LIMIT	PLASTIC INDEX	WATER CONTENT (%)	DRY DENSITY PCF	UNCONFINED COMPRESSIVE STRENGTH	DEGREE OF EROSION
Ross Ck.	1	1000' west of Jarvis	4	Lt. brn. sandy clayey silt (ML)	21	5				Moderate
	2	1000' west of Jarvis	10	Lt. brn. sandy gravel (GW)						Slight
	3	200' west of Cherry	9	Lt. brn. sandy clay (CL)						Moderate
	4	200' west of Cherry	10	Lt. brn. sandy clay (CL)	29	11				Moderate
Sierra Creek	1-1	Sta 1 + 00	10	Lt. brn. sandy clay (CL)	44	26	9	106	14,290	Moderate
	1-2	Sta 1 + 00	8	Dk. brn. sandy clay (CL)	38	20	19	102	2,170	Slight
	2	Sta 10 + 00	8	Lt. brn sandy clayey silt (ML)	36	12				Slight to Moderate
	3	Sta 12 + 00	8	Sandy gravel (GW)						Slight
	4-1	Sta 44 + 00	9	Brn. clayey sand (SC)	32	14	12	97	740	Slight to Moderate
	4-2	Sta 44 + 00	9	Brn. clayey sand (SC)						Slight to Moderate
Smith Creek	3-1	100' north of Elam	12	Lt. brn. clayey gravel (GC)						Very Slight
	3-2	100' north of Elam	8	Lt. Brn. clayey sand (SC)						Very Slight
	4-1	500' north of Elam	9	Brn sandy clay (CL)	37	18	11			Slight to Moderate
Golf Creek	1	Between Redwood & Almaden *		Dense sandy gravel (GW)						Moderate
	2	Between Redwood & Almaden *		Brn Sandy Clay (CL)						Moderate
Calabazas	1-1	300' east of Kifer	8	Lt. gray-Brn., V. clayey sand (SC)	32	15	20	105	2,510	Severe
	1-2	300' east of Kifer	2	White silty clay (CL)	42	24	19	104	10,940	Severe
	1-3	300' east of Kifer	5	Tan clayey silty sand (SM)						Severe
	2-1	600' west of Kifer	5	White sandy clay (CL)	32	18				Severe
	2-2	600' west of Kifer	8	Brn-gray silty clay (CL)	37	21	18	106	5,030	Severe
	3-1	500' north of Monroe	5	Brn. V. clayey sand (SC)	39	23				Severe
	3-2	500' north of Monroe	8	Lt. Brn.-gray sandy clay (CL)	43	26	19	103	9,070	Severe
	4-1	300' north of Monroe	5	White sandy clay (CL)	37	20				Severe
	4-2	300' north of Monroe	8	Lt. Brn.-gray clayey sandy silt (ML)	39	20	25	96	2,610	Severe
	5-1	1000' north of Benton	8	Lt. Brn.sandy clay(CL)	34	16	19	98	2,170	Moderate
	6-1	1000' west of Pomeroy	8	Lt. Brn. clayey sand (SC)						Severe
	6-2	1000' west of Pomeroy	14	Dk. Brn. gravelly clay (CH)	56	35				Severe
	7-1	400' west of Pomeroy	8	Lt. Brn. clayey sand (SC)			9	130	5,960	Slight Moderate
	7-2	400' west of Pomeroy	12	Dk. Brn. gravelly clay (CL-CH)	48	29	14	107	12,120	Slight Moderate
Sunnyvale East Channel		El Camino Real to Bayshore Freeway*	0-3	Blk silty clay						Severe
			3-9	Lt. Gray-Brn. silty Clay with lime cementation						Severe
			9	Lt. Brn. clayey sand						Severe

* Idealized soil conditions

** Depth Below Surface

TABLE II

VELOCITIES AND TRACTIVE FORCES OF SANTA CLARA COUNTY FLOOD CONTROL AND WATER DISTRICT CHANNELS

CREEK AND SAMPLE	MAXIMUM FLOW (CFS) (Q)	DEPTH AT MAXIMUM FLOW (FT) d	CHANNEL SECTION AS BUILT b$^{(1)}$	z$^{(2)}$	s$^{(3)}$	VELOCITIES$^{(4)}$ (ft/sec) Max.developed	Allowable	DEVELOPED TRACTIVE FORCE (PSF) BOTTOM (T_b)	SIDE (T_s)	ALLOWABLE TRACTIVE FORCE (PSF) BOTTOM (T_b)	SIDE (T_s)
Ross	760	5.1	8'	1-1/2:1	.0039	9.5					
1							4.0	0.770	0.645	0.40	0.40
2							3.1	0.740	0.619	0.25	0.10
3							4.0	0.770	0.645	0.44	0.44
4							4.0	0.770	0.645	0.36	0.36
Sierra		3.0 (assumed)	6'	1-1/2:1	.0059	8.0					
1-1							4.0(max)	0.710	0.582	0.38	0.38
1-2							4.0	0.710	0.582	0.50	0.50
2							4.0	0.710	0.582	0.36	0.36
3							2.7	0.781	0.641	0.32	0.13
4-1							4.0	0.710	0.582	0.50	0.50
4-2							4.0	0.710	0.582	0.12	0.12
Smith	300 (est)	4.0	8'	1-1/2:1	.0013	4.0					
3-1							4.1	0.206	0.168	0.56	0.22
3-2							4.0	0.216	0.176	0.005	0.005
4-1							4.0	0.216	0.176	0.45	0.45
Golf	250	2.5	8'	1-1/2:1	.005	7.7					
gravels							4.0-5.0	0.740	0.585	0.40	0.16
clays							2.5-4.0	0.535	0.422	0.20	0.20
Calabazas	800	4.8	10'	1-1/2:1	.004	9.7		0.746	0.612		
1-1							4.0	0.768	0.560	0.17	0.17
1-2							5.5			0.50	0.50
1-3							4.0			0.17	0.17
2-1							4.0			0.49	0.49
2-2							5.5			0.49	0.49
3-1							5.5			0.28	0.28
3-2							5.5			0.42	0.42
4-1							5.5			0.42	0.42
4-2							5.5			0.44	0.44
5-1							4.0			0.42	0.42
6-1							4.0			0.20	0.20
6-2							5.5			0.50	0.50
7-1							4.0			0.20	0.20
7-2							5.5			0.50	0.50

b$^{(1)}$ - bottom width (feet)

z$^{(2)}$ - side slope (horz/vert)

s$^{(3)}$ - bottom slope (feet/foot)

(4) - permissible velocities obtained from charts and table developed by Forteer and Scobey, shown as Fig. 6-1 in TR25 of the S.C.S for suspended load